Groyne field nourishments

A research into the application of feeder nourishments to supply sediment to the main channel

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by

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Abstract

In the Waal bed degradation occurs, which is mainly induced by a large number of river regulations measures done in the past. Rijkswaterstaat develops possible measures and new techniques to stop riverbed erosion and/or mitigate the negative effects. One of the possible new techniques to reduce riverbed erosion locally is groyne field nourishments.

The objective for this research is to deepen insights how groyne field nourishments provide enough sediment to the river such that bed degradation locally does not develop further. The following research question is formulated for this: How can groyne field nourishments act as small feeder nourishment that release sediment slowly to the main channel? To answer the research question a literature study is done and a XBeach model is set-up.

The literature study is done to obtain knowledge about the hydrodynamic and morphodynamic processes in a groyne field in case of emerged and submerged groynes. From this literature study it appears that the effect of navigation on the morphology in a groyne field is dominant over the effect of the river discharge when the groynes are emerged: net sediment is transported from the groyne field to the main channel mainly by suction. When the flow conditions increase and the groyne get submerged, the effect of navigation on the morphology in the groyne field decreases rapidly and the net sediment transport is from the main channel to the groyne field induced by the river discharge, mainly the large-scale eddies.

Extra literature study is done to possible relevant coastal and river processes to get knowledge of the effects of waves and currents on the behaviour of nourishments in a groyne field since very limited research has been done before on groyne field nourishments. It appears that especially dune erosion and river bank erosion by waves and currents can be used to explain how nourishments erode by the primary and secondary ship wave system.

After the literature study a XBeach model is set-up of for a series of emerged groynes on a straight section in the Waal. The model is calibrated and validated with data from Rijkswaterstaat and literature. In this model three possible nourishments with the same volume are applied at different locations in the groyne field: 1) one upstream in the groyne field; 2) One downstream in the groyne field; 3) And one in the middle of the groyne field.

From this research it can be concluded that groyne field nourishment at all three locations can work as small feeder nourishment that release sediment slowly to the main channel in the case of emerged groynes for about 200 days per year. The nourishment placed in the centre of the groyne field appears to be the most effective nourishment, since 1) the waves and currents induced by navigation attack the nourishment along all its edges, 2) the centre nourishment causes in almost the whole groyne field an increase of sediment transport to the main channel and 3) the flow pattern in the groyne field is changed favourably for the sediment transport of already suspended sediment to the main channel.

This research should be seen as first indication if nourishment could work at all. It is advised to research the material of the nourishment and to simulate the groyne field nourishments for a longer period, such that more flow conditions and more ship passage are included, to get a more complete picture of how groyne field nourishments act as small feeder nourishments. Furthermore a practical test with a centre nourishment is recommended to collected data of the hydro- and morphodynamics in a groyne field with nourishment.

Keywords: Groyne field, nourishment, bed degradation, Waal, navigation, ship waves, primary waves, secondary waves, return current, supply flow, suction, river discharge, large-scale horizontal eddies, unidirectional flow, river bank erosion, dune erosion, avalanching, negative feedback process, sediment transport, XBeach, numerical modelling

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1. Introduction

The Dutch Ministry of Infrastructure and Water Management will launch a program called Integral River Management (IRM) in 2029. This program is set up, among other things, to work on riverbed erosion in the Dutch rivers. Rijkswaterstaat contributes to the IRM program and will develop possible measures and new techniques to stop riverbed erosion and/or mitigate the negative effects.

One of the possible new techniques to reduce riverbed erosion is groyne field nourishments. These sediment supplements dumped in a groyne field may act as small feeder nourishments that release sediment slowly such that they can compensate for shortage of sediment supply to the river. In this way the river bed degradation may reduce.

This report contains the master thesis researching how groyne field nourishments can act locally as small feeder nourishments.

The introduction contains the approved research proposal which presents the context, problem definition, objective, research and sub-research questions and the methodology.

1.1 Context

After the “Room for the River” program aimed at, amongst others, creating more space for the rivers to discharge water safely, The Dutch Ministry of Infrastructure and Water Management will launch the Integral River Management (IRM) program in 2029. This program is focused on improving the following functions of the Dutch rivers:

- Water safety
- Water quality
- Water-borne transport
- Water availability

This improvement of functions should be achieved in a sustainable and efficient way and should also include the needs of stakeholders. One of the reasons this program is set up is riverbed erosion, which occurs in the upper Rhine branches in the Netherlands. In table 1.1 the large-scale river bed erosion is quantified for the upper Rhine and the Waal.

Table 1.1: Average bed erosion of the Upper Rhine and the Waal based on the trend of the past 5 years, between brackets the river km (Ylla Arbos et al., 2019)

Boven-Rijn (858-867)	1.2 cm/year
Boven-Waal (867-890)	1.4 cm/year
Midden-Waal (891-915)	1.3 cm/year
Beneden-Waal (916-925)	1.2 cm/year

Rijkswaterstaat participates in the IRM program and will develop over the coming 10 years measures and techniques to deal with this erosion. When developing this approach the building with nature philosophy is considered. “Building with Nature” is based on taking the natural system as the starting point of a project and makes use of natural processes (wind, currents, natural materials) when designing measures (Ecoshape, n.d.). In this program a measure needs to be designed to stop riverbed erosion or mitigate the negative effects.

One of the possible new techniques is groyne field nourishments. The idea is that these nourishments provide enough sediment to the river such that bed degradation locally does not develop further.

An occurrence of bed degradation is found downstream of the sharp bend with the fixed layer in the Waal at Nijmegen. In the following the characteristics and the history of the Waal will be elaborated to get more insight in the cause of bed degradation in the Waal and the problems it causes.

Bed degradation in the Waal

The Rhine bifurcates into the Waal and the Pannerdensch Kanaal and about 2/3 of the Rhine discharge flows into the Waal. The Waal is the most water rich branch of the Rhine. The Waal is meandering through the landscape and contains some sharp bends and has a length of 85 km. It is the main river for navigation in The Netherlands, because it connects the harbour of Rotterdam to the hinterland of Germany.

The degradation problems in the Waal are mainly induced by a large number of river regulations measures taken to improve the living conditions along the Waal. In appendix A.1 the history of the Waal is elaborated in detail. The effects of the river regulation measures taken will be explained below.

Until 1850 multiple river regulation measures were done to protect against floods: dikes were constructed and groynes were applied to protect the dikes from erosion. Furthermore, to prevent dike breaches by ice jams in shallow areas, the flow in the river was increased by closing of secondary channels, cutting off river bends and placing additional groynes. Another effect of these measures was that the main channel of the river was deepened by erosion, which was beneficial for navigation (Smedes et al., 2006).

The main channel was deepened, among others, by placing series of groynes. These groynes are blocking the flow near the river banks and the flow velocity therefore increases in the centre of the river. As a consequence the bed shear stress increases in the main channel, which leads to erosion of the bottom material and finally the deepening of the main channel.

The series of groynes together form a long constriction in the Waal, which cause an increase of the water depth and reduction of the bed slope (the relative increase in the water depth is larger than the relative reduction of the slope) (De Vriend, Havinga, Van Prooijen, Visser, & Wang, 2011). By adjusting the length of the groynes the equilibrium bed level in the river can be changed locally (Uijttewaal, 2007).

In figure A.1 the top panel shows the Waal in 1817 after measures described above: the width of the main channel was normalized and narrowed. The next river regulations measures were two large scale width normalisations, the first one between 1850 and 1888 (middle panel in figure A.1 and the second one between 1888 and 1890 (bottom panel in figure A.1 (Ten Brinke, 2004).

After these two normalisations it appeared that the cut-offs enhance bed degradation in the Waal, which became problematic for navigation in the Pannerdensch Kanaal. Future cut-offs were dismissed and other river improving measures need to be evaluated.

At the end of the 20th century it was planned to allow bigger ships (6-barge push-tows) on the Waal. The Netherlands and Germany set up a program to achieve this: the Waal Project. The objectives of the Waal Project were (Smedes et al., 2006):

- Increase main channel dimensions to 170 m x 2.80 m at OLR (agreed low water level);
- Stop bed degradation, because the riverbed degraded with several cm per year;
- Obtain surplus values for the river’s ecosystem by integrating floodplain rehabilitation plans.

Increasing the main channel dimensions and improving the navigability of the Waal is achieved, among others, by constructing a fixed layer at the bend of the Waal near Nijmegen. In appendix A.2 the effect of the fixed layer on the river bed is explained in detail.

The most recent river regulating measures are the lowering of the groynes in the Waal between Nijmegen and Gorinchem, to decrease the water level in the Waal during high water and the construction of longitudinal dams to reduces sedimentation so that less dredging works are needed.

The river bed degradation is a major concern, because structure like the fixed layer and locks do not lower with the bed. Due to the continuing degradation these hard points in the river increasingly become bottlenecks. Navigation will not be able to pass these hard points during low water conditions and therefore the loading capacity decreases. Until now the negative effects of the hard points are compensated by dredging works or other short-term measures. But when large scale bed degradation in the Waal and the Upper Rhine will not be reduced these hard points will be bottlenecks for navigation within a couple of years. So a durable solution against the bed degradation would be ideal.

Groyne field nourishments

Groyne field nourishments will be explored in the IRM program to compensate for the channel bed degradation in the Waal. Nourishments in the main channel will create hindrance for navigation and therefore nourishments in the groyne fields are proposed. The nourishments may function as a small feeder nourishment that releases sediment slowly.

When nourishments are applied in the Waal, these nourishments will be located in the area between the groynes, the groyne fields. In figure 1.1 a typical cross section of the Waal can be seen. The groyne field is located at the slope between the groyne heads and the 'beach'. The term 'Beach' is used because groyne fields largely act and look like a coastal beach. The width of the beaches is influenced by the flow conditions of the Waal, during low water the average width of the beach is 25 m, but also widths of 100 m are observed (Ten Brinke, 2004). The beaches at the inner bends of the river are the widest due to natural sedimentation occurring in the inner bends.

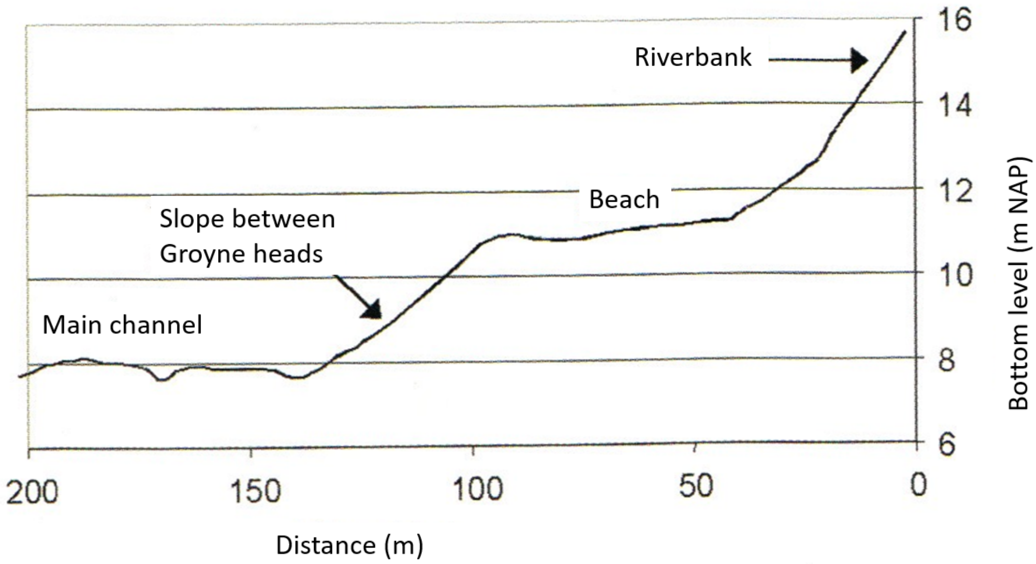


Figure 1.1: Cross-section of the Waal (Ten Brinke, 2004)

Groyne fields retain sand during low and normal flow conditions, because then the groyne fields are out of reach of the river flow. Therefore a steep slope occurs between the groyne fields and the main channel.

The intended purpose of groyne field nourishments is to stop bed degradation locally. A lot of factors can influence the way a groyne field nourishment act as a small feeder nourishment. For example the nourishment material: relative coarse sediment, compared to the bed surface sediment, has a stabilising effect by armouring the bed surface, but it also tends to cause degradation problems further downstream (Emmanouil, Blom, Viparelli, & Frings, 2017). When too fine sediment is added to the groyne field and this sediment is transported to the main channel, the mobility of coarser particles in the main channel bed is increased and degradation is enhanced.

Furthermore the flow conditions in the river determine, among others, where the material of the nourishment is transported to. For example during high water the material may be transported to the floodplain, the opposite of what is actually intended through groyne field nourishments.

Figure 1.2 shows the possible directions of transport of the nourishments with the yellow and orange arrow.

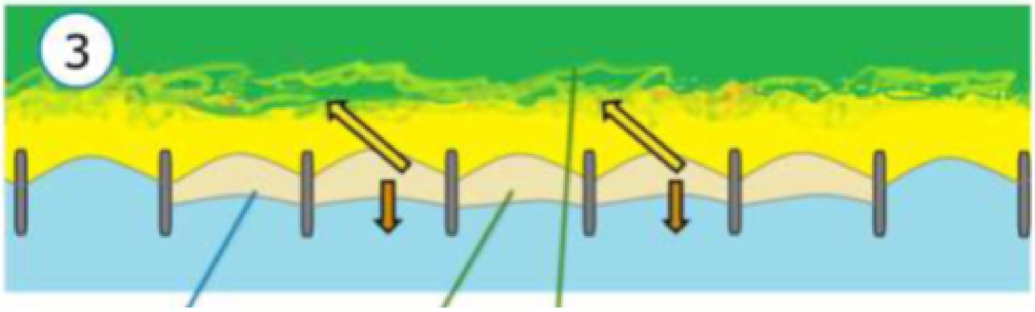


Figure 1.2: Possible transport directions of the nourished material

To explore how groyne field nourishments may function as small feeder nourishments a number of questions need to be researched. For example: What are the morphological processes in the groyne field after a nourishment is placed? What is the effect of different types of groyne field nourishments? What is the effect of the material, the location or the dimensions of the nourishments? What will happen during low water and high water conditions? How long does it take for the nourished sediment to fully erode and what parameters do influence that erosion? Further, is this an effective and efficient measure for bed degradation and can this measure be implemented at other locations?

A couple of questions are chosen to focus on in this research. These will be highlighted in the next section.

1.2 Objective and research questions

Problem definition

In the Netherlands multiple rivers experience continuing bed degradation, especially the branches of the Rhine. A durable solution for this problem is asked for. By researching groyne field nourishments, a new measure against bed degradation can be suggested.

Nowadays it is not known if groyne field nourishments can act as small feeder nourishments that release sediment slowly. It is therefore important to determine how sediment is transported from a groyne field to the main channel of a river and the other way around.

Objective

The objective for this research is to deepen insights how groyne field nourishments can act as small feeder nourishments that release sediment slowly.

Research question

The research question for this master thesis is defined as: *How can groyne field nourishments act as small feeder nourishments that release sediment slowly to the main channel?*

To answer this research question, the following sub-research questions are formulated:

1. Which morphodynamic and hydrodynamic processes play a (predominant) role in the dynamic equilibrium of a groyne field?
2. Which new processes will be induced or which processes, that maintain the dynamic equilibrium in a groyne field, will become more pronounced/relevant by placing a nourishment in a groyne field?
3. How does the type of nourishment (shape and location) influence the way in a nourishment will act as a small feeder nourishment that slowly releases sediment to the main channel?

1.3 Methodology

In this section the methodology of the research will be explained. At first, the methodology for each sub-research question is elaborated.

Sub-research question 1

Which morphodynamic and hydrodynamic processes do play a (predominant) role in the dynamic equilibrium of a groyne field?

To be able to answer this question a literature study regarding hydrodynamics and morphodynamics in groyne fields is undertaken. Furthermore, a visual inspection is done by visiting groyne fields along the Waal downstream of Nijmegen during high water (submerged groynes) and low water (emerged groynes). Videos and photos are taken to assess the hydrodynamic and morphodynamic processes.

Sub-research question 2

Which new processes will be induced or which processes, that maintain the dynamic equilibrium in a groyne field, will become more pronounced/relevant by placing a nourishment in a groyne field?

To answer this question a literature study is required. It is expected that very limited research is done on groyne field nourishments acting as small feeder nourishments. It seems that technical reports and/or scientific articles in this field are very scarce. To tackle this issue, possible relevant coastal processes will be researched to get knowledge, for example, of the effects of waves and currents on the behaviour of nourishments. Also bank erosion processes could be relevant.

Through literature study an initial understanding is obtained on the hydrodynamics and morphodynamics affecting the placed nourishment and also some promising nourishment locations may be defined. To test this initial understanding and to finally achieve the research objective, it is mandatory to create a model of a groyne field in a software tool.

First a base case will be set up for the start situation: a groyne field without a nourishment. In chapter 4 the setup of the base case and the validation procedure will be presented in detail. To set up the base model the dominant processes of the hydrodynamic and morphodynamic processes that play a role in the dynamic equilibrium of a groyne field, are obtained from sub-research question 1. This will be an important part of this research.

Furthermore information about useful software tools is acquired. A literature study will therefore specifically look at identifying suitable software and applicable simulation solutions that can model the dominant hydrodynamics and morphodynamics of rivers and coasts on a relatively small scale. Since software tools are mostly focused on rivers or coasts for different time and spatial scales it is expected that the presented models need to be adapted or alternative applications of the models need to be undertaken. For this research XBeach and Delft3D will be considered.

Before being able to set up a model in the selected software tool, it is necessary to get familiar with the software through documentation and experimenting with the functions of the software. Also Royal HaskoningDHV and Deltares will be asked for support in using the software tool.

To obtain an accurate base model data is required of the river characteristics, the navigation characteristics, the hydrodynamics and the morphodynamics. Rijkswaterstaat will be approached to gather relevant data. Furthermore data can be found in literature.

This data will be used to set up the model (for example the domain, the bathymetry and the hydrodynamic forcing) and to validate the model results (for example the water level, flow velocities and the bed shear stress). Depending on the relevance and quality of the available data, the model results can be validated quantitatively or qualitatively (exact or order of magnitude).

To be able to distinguish the effect of different hydrodynamic and morphodynamic processes on the model results several factors like water level, hydrodynamic forcing components, river discharge and ship waves are switched on and off one by one to validate a specific process. Furthermore the complexity of the model will be increased during the validation process: at first only the hydrodynamics are simulated, when the model appears accurate for small grid sizes and the required modelling calculation time permits, the sediment transport is added and thereafter the morphodynamics may be included. Here it should be kept in mind that morphodynamic prediction by software tools is still very much in development.

After the base model is validated it is known which hydrodynamic and probably morphodynamic processes are simulated accurately and where the limitations of the model come forward. This information should be taken into account when assessing the model results.

Based on the initial thought on the hydrodynamic and morphodynamic processes occurring in a groyne field after a nourishment is placed, a nourishment will be added to the base model.

Sub-research question 3

How does the type of nourishment (shape and location) influence the way in a nourishment act as small feeder nourishment?

To answer this sub-research question the model from sub-research question 2 will be used. A couple of nourishment locations and shapes will be tested to show the possible differences between, among others, flow patterns, bed shear stress and sediment transport rates. The material and the volume of the nourishment will be kept constant to make an educated guess for these parameters. Furthermore the flow conditions will be defined once and used for all simulations regarding the types of nourishment to be used. The flow conditions will be defined such that it is expected to see the clearest difference between the model results of the different nourishments. Finally the model settings will also be constant. In this way the types of nourishment can be compared in the best way.

The model results of the three nourishment options will be compared and the differences will be assessed as far as possible considering the literature study done for sub-research question 1 and 2. From this assessment an advise to Rijkswaterstaat will be defined regarding the locations that seem to be suitable for placing nourishments that it will supply sediment to the main channel of the river.

2. Hydro- and morphodynamic behaviour in groyne fields

In this chapter the hydrodynamic and the morphodynamic processes that play a role in the dynamic equilibrium of the bathymetry in groyne fields will be elaborated. The dynamic equilibrium is maintained by the interaction between the groyne fields and the main channel, consisting of two main components:

- River discharge
- Navigation

In the following first the dynamic equilibrium of a groyne field is further explained. Thereafter the two components are elaborated in detail.

2.1 Dynamic equilibrium

The beach between the two groynes continue to exist due to presence of a long term (decades) dynamic equilibrium: the erosion of sand during low flow conditions balances with the sedimentation during high flow. During low to middle flow conditions the groynes are emerged and during middle to high flow conditions the groynes are submerged. It depends on the groyne height during what flow conditions the groynes get submerged.

When the groynes are emerged, the erosion of sand of beaches and/or river banks in groyne fields is caused by waves and currents due to river discharge and navigation. The river discharge causes large-scale circulation (eddies) in a groyne field. This circulation mainly contributes to sediment transport by importing sediment from the main channel. The circulation can also cause sediment transport out of the groyne field, but the turbulence and currents induced by the circulation are often too weak to mobilise sand from the groyne field bottom.

Meanwhile passing ships induce waves and strong currents into the groyne field which mobilise and transport sand and therefore have a significant share on the erosion of groyne fields. The large-scale circulation due to the river discharge can transport the sediment already mobilised by ship waves.

The combined effect of the sediment transport by river discharge and navigation in case of emerged groynes can be seen in figure 2.1. It shows that the eroding effect of navigation is dominant over the aggrading effect of the river discharge, which leads to a continuous degradation in the groyne fields when the groyne are emerged.

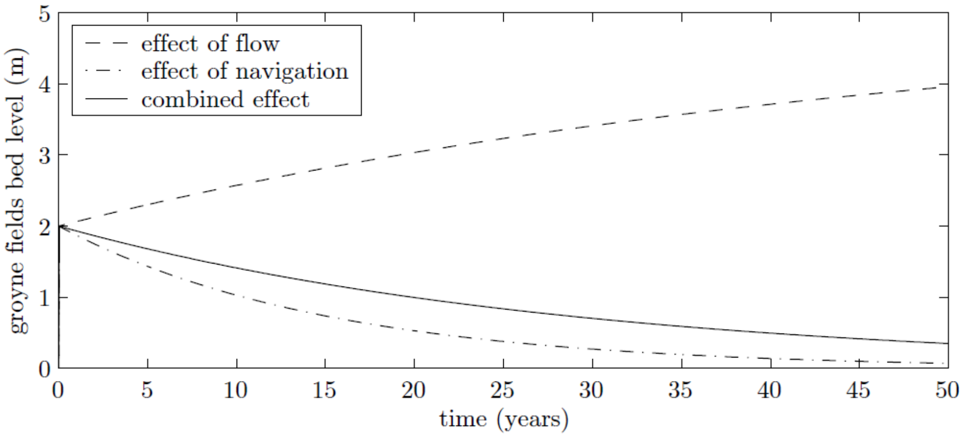


Figure 2.1: Combined effect on bed development of groyne field for low and normal flow conditions in the Waal (Yossef, 2005)

When the river discharge gets higher and the groynes become submerged the effect on the sediment transport of the river discharge gets dominant over the effect of navigation. In this circumstance the erosion of the groyne field bed during low flow conditions is compensated by a great sediment supply due to a high discharge.

When the groynes are submerged, sediment is imported into the groyne field by advective transport induced by large-scale coherent structures and the diffusive transport induced by the mixing layer over the groyne. The degree of sedimentation in the groyne field depends on the duration of a high discharge (Yossef, 2005).

In figure 2.2 the effect of high waters with a return period of 5 years and the amount of erosion during 5 years are considered. It can be seen that the sedimentation, in the case of submerged groynes, and the erosion, in case of emerged groynes, more or less compensate.

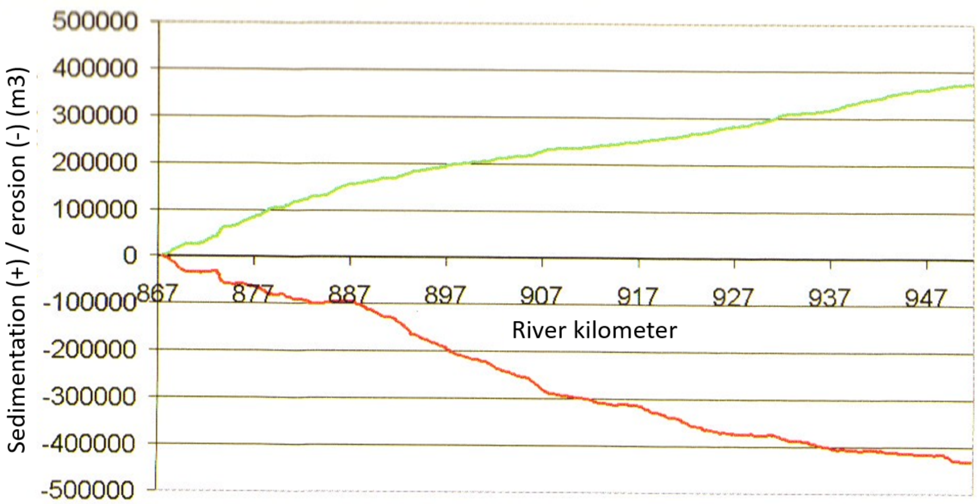


Figure 2.2: Cumulative sedimentation (green) and erosion (red) on groyne field beaches along the Waal (Ten Brinke, 2004)

In the left panel of figure 2.3 the discharge at Lobith is shown and in the right panel both the gradual erosion in case of an emerged groynes, and the quick sedimentation in case of submerged groynes can be seen. The right panel is based on the measured data from the left panel. The high water periods that are marked red in the figure occur once in five years. During these high water periods quick sedimentation occurs in the groyne field as can be seen in the right panel. During lower water periods (blue line in the left panel) gradual erosion occurs in the groyne field, shown in the right panel. When looking over a period of 30 years, in which even the navigation intensity increased, it can be seen that the groyne field beaches tend to breath: periods of erosion and sedimentation alternate, but the groyne field beaches stay within a dynamic equilibrium.

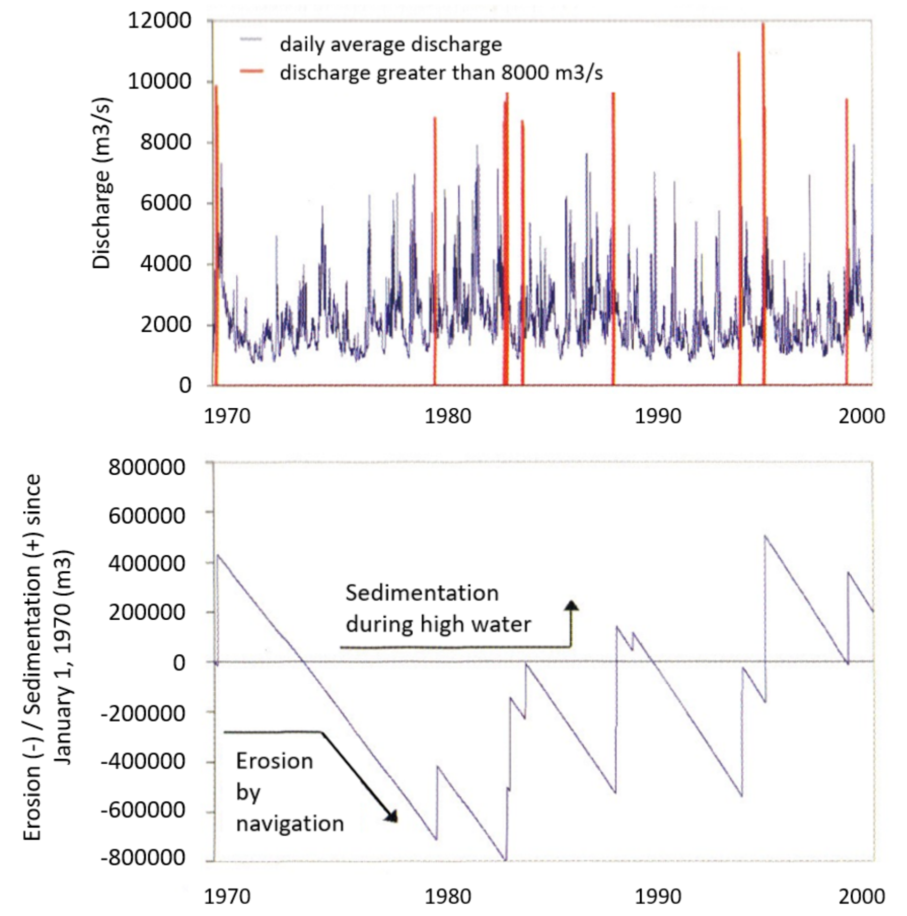


Figure 2.3: Top: Discharge at Lobith, Bottom: erosion and sedimentation (Ten Brinke, 2004)

The degree of erosion of a groyne fields is not equal among the groyne fields. A significant difference, amongst others, can be observed between the erosion of groyne fields along the northern side and along the southern side of the Waal. Heavily loaded ships sail from along the southern river bank to Germany and return empty or less loaded along the northern river bank. Heavier ships cause larger currents and therefore more erosion in groyne fields. The erosion of the southern river side is about two times the erosion of the northern river side (Ten Brinke, 2004). Also the intensity of the navigation is an important factor in the amount of erosion of groyne fields.

In the following sections the hydrodynamics and the morphodynamics playing a role in the dynamic equilibrium will be further elaborated.

2.2 River discharge

In this section the effect of river discharge on the hydrodynamics and the morphodynamics in a groyne field are determined.

In appendix B general flow hydrodynamics (flow loads and flow separation) and in appendix C general flow morphodynamics (Flow stability, sediment transport) are briefly explained. The definitions related to these general hydro- and morphodynamics will be used to explain the flow hydrodynamics and morphodynamics in a groyne field.

Hydrodynamics

In this paragraph the flow pattern in groyne fields will be discussed for emerged groynes and submerged groynes.

Emerged groynes

In a state of emerged groynes, the flow pattern in a groyne field is only indirectly affected by the main stream of the river, because the groyne field is not a part of the wetted cross section of the river that discharges (Yossef, 2002).

The main flow diverts with a low velocity from the main channel into the groyne field. At the downstream part, the water flows into the groyne field, because the main flow cannot make the sharp bend into the groyne field directly after the upstream groyne. At the downstream groyne of a groyne field, water flows back into the main channel or the water starts circulating in the groyne field. This circulating pattern is called an eddy. The circulation is driven by the momentum exchange through the mixing layer (Ten Brinke, 2003).

When the distance between two groynes is more than 200m or when the width/length ratio of the groyne field is about 3, the eddy becomes elongated and separates from the river bank. This provides room for a secondary eddy rotating in the opposite direction. The secondary eddy gets its momentum from the primary eddy by an intermediate mixing layer. The single-eddy and the double-eddy pattern can be seen in figure 2.4 (Ten Brinke, 2003). The secondary eddy is located in the downstream corner near the river bank. With this geometry a stable circulation is obtained in which the primary eddy flows smoothly at about 30% of the main stream velocity and the secondary eddy flows with a velocity of about 30% of the speed of the primary eddy.

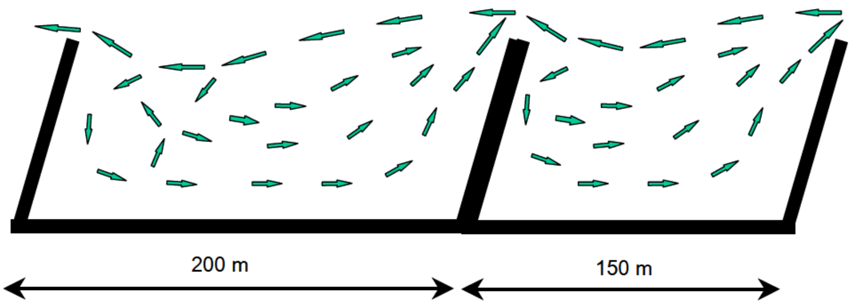


Figure 2.4: Flow pattern in groyne field (Ten Brinke, 2003)

In figure 2.5 the double-eddy pattern is shown in more detail. The primary eddy is located downstream of the upstream groyne in the first three-quarters of the groyne-field. The pivot of the primary eddy is not at the centre of the eddy, but it is close to the tip of the upstream groyne. This is because of the dynamic eddy, which is shedding intermittently and migrates along the inter-facial line between the main flow and the primary eddy. The dynamic eddy eventually merges with the primary eddy (Yossef, 2005).

The figure shows also the secondary eddy upstream of the second groyne.

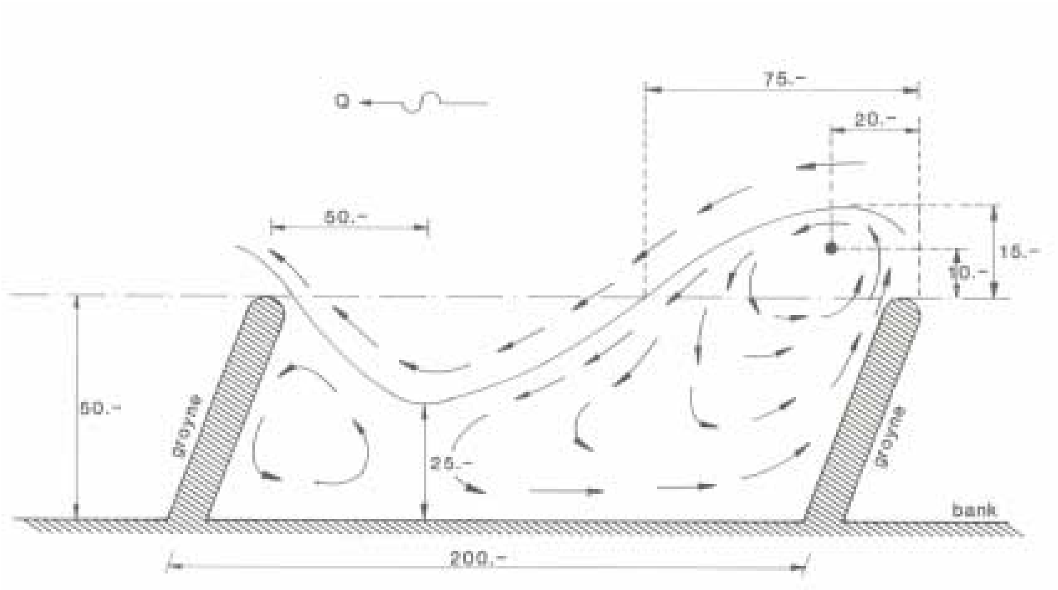


Figure 2.5: Flow pattern in groyne field (Yossef, 2002)

In D.1 other flow pattern types in a groyne field between emerged groynes can be found, these types of patterns may occur for example at bend parts in the river.

The flow pattern between two emerged groynes is predominantly two-dimensional: the large-scale horizontal eddies. In addition, small-scale three-dimensional turbulence (horse-shoe vortex and wake vortex system) along the groyne and large-scale three-dimensional structures (migrating vortices) occur near the groyne head (Yossef, 2005).

Submerged groynes

When the water level increases the groynes become submerged and water starts to flow over the groyne crest. For submerged groynes the hydrodynamics are different compared to the hydrodynamics around emerged groynes.

When the groyne is getting submerged the horizontal circulating flow pattern of the emerged case interacts with the unidirectional flow in the top layer. Therefore the momentum balance in the groyne field has two sources: large-scale horizontal eddies and the unidirectional flow. These two components can cause a strongly fluctuating flow field when they are of the same order of magnitude (Uijttewaal, 2007).

The flow pattern for submerged groynes depends on the extent to which the groyne is submerged. When groynes are just submerged the large horizontal eddies will be damped, a sketch of the flow pattern for a small submergence is given in figure 2.6 in the right panel. During high submergence levels the horizontal eddies will disappear and the flow over the groyne will get stationary with almost parallel streamline. A sketch of the flow pattern for a full submergence is given in figure 2.6 in the left panel.

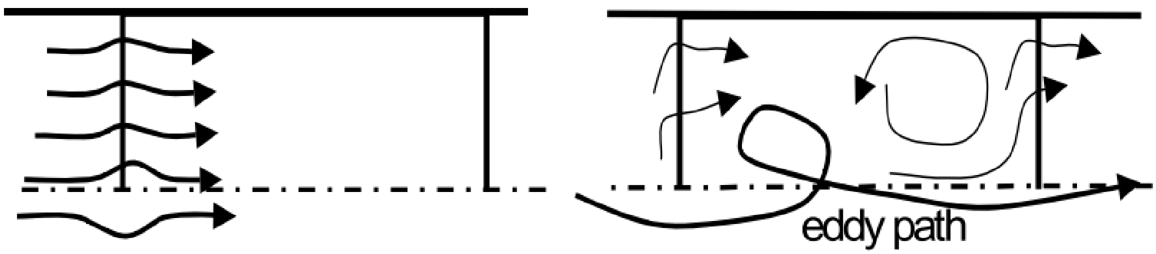


Figure 2.6: Flow patterns for submerged groynes. Right: fully submerged, Left: small submergence (Uijttewaal, 2007)

Downstream of the groyne crest higher flow velocities occur due to vertical flow separation (explained in appendix B.2). The vertical flow separation is shown in figure 2.7, the water flow is from left to right. The flow separation downstream of the groyne keeps the flow in the surface layer at a high velocity.

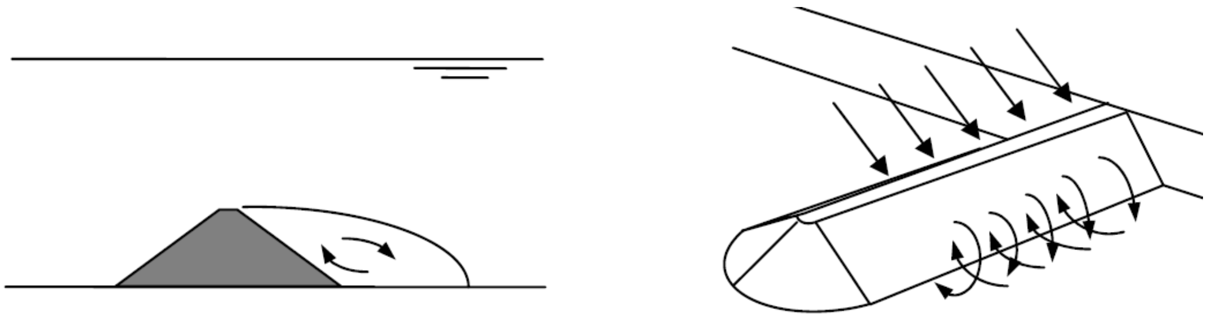


Figure 2.7: Recirculation zone for straight incoming water flow (left) and for oblique incoming water flow (right) downstream of a submerged groyne (Van Broekhoven, 2007)

Another aspect of the submerged flow pattern is the formation of a secondary flow structure. Both on top and behind the groynes there is a secondary circulation that is directed from the bank towards the channel axis near the surface, and the other way around near the bed (Yossef, 2005).

For emerged and submerged groynes the flow pattern in the groyne field is influenced by the following parameters:

- **Spacing–length ratio (S/L)**: The spacing-length ratio determines the number and shape of the horizontal eddies that form along the normal line and inside the groyne fields. When the ratio is about 1 a single eddy develops. A larger aspect ratio indicates there is room for two eddies. An extremely long groyne-field leads to the penetration of the main flow into the groyne-field (Yossef, 2005).
- **Spacing–height ratio (S/hg)**: The spacing-height ratio governs the flow pattern in the vertical plane. When the groynes are spaced far apart the flow that separates from the upstream groyne reattaches to the bed. Too closely positioned groynes will prevent the flow reattachment to the bed, thus keeping the bed shear stress low (Yossef, 2005).
- **Side slopes**: The dynamics of the flow and the strength of the eddies detaching from the tip of the groynes strongly depend on the slope (Yossef, 2005).

Mixing layer

The mixing layer between the main channel and the groyne fields differ in nature between the emerged and submerged flow stages. In figure 2.8 the mixing layer can be seen for emerged groynes (A1) and for submerged groynes (A2 and A3). In the figure the water flows from bottom to top. The solid horizontal line represents the location of the groyne. The head of the groyne is sloped, so the two solid vertical lines at represent: the top of the slope (Y=3.5 m) and the bottom of the slope (Y=3 m). The dashed vertical lines indicates the mixing layer shape (Yossef & De Vriend, 2011). Downstream of the groyne no measurements were done therefore this area shows no velocities.

In the emerged situation the mixing layer originates from the tip of the groyne and grows in width towards the next groyne downstream.

In the submerged situations the mixing layer develops between the fast stream in the main channel and the slow stream in the groyne fields region due to the steep velocity gradient. The mixing layer has a constant width, because the water flows along a series of groynes, which keeps the velocity difference between the fast stream (main channel), and the slow stream (groyne field) almost constant. This constant velocity difference maintains a constant velocity gradient across the mixing layer and therefore keeps the mixing layer width also constant.

A comparison between the two submerged cases, A2 and A3 shows that with increasing submergence, the magnitude of the total turbulence intensity and the transverse shear stress decreases, while the width of the mixing layer remains the same. (Yossef & De Vriend, 2011)

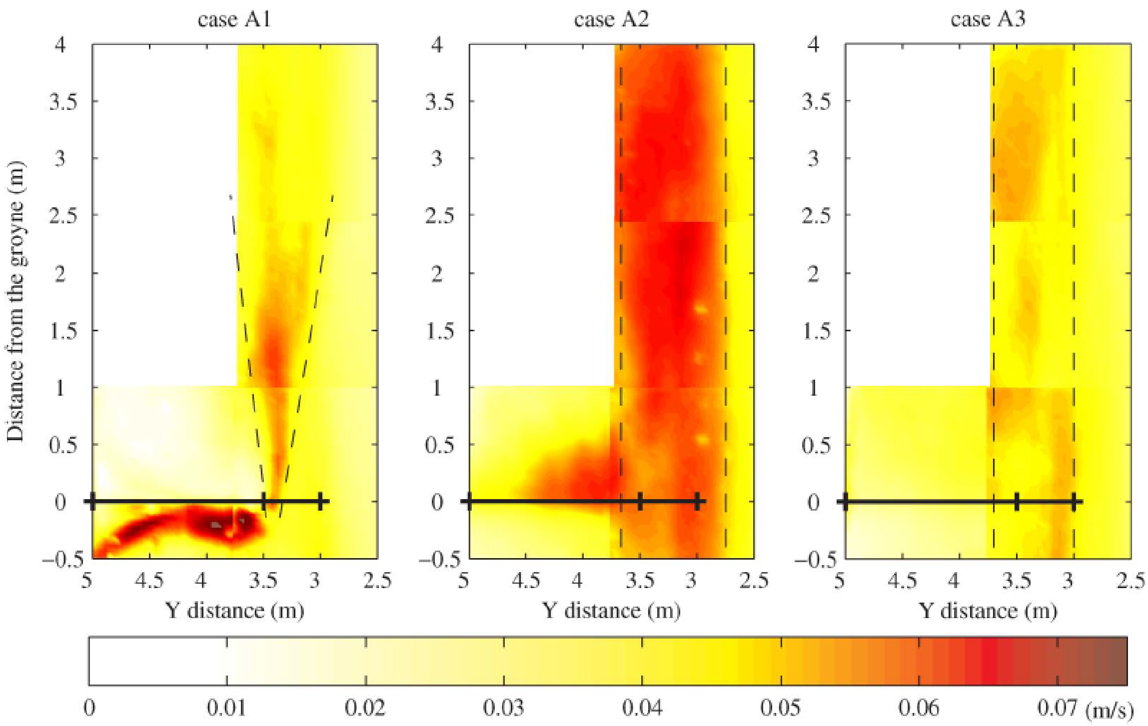


Figure 2.8: Mixing layer in the case of emerged groynes (A1) and submerged groynes (A2 and A3). Low submergence level (A2), high submergence level (A3) (Yossef & De Vriend, 2011)

Morphodynamics

In this section the morphodynamics will be discussed for the main channel and the groyne fields in case of emerged and submerged groynes. For an intermediate scale the effects of a series of groynes on the morphology of the main channel can be determined. The morphodynamics on a small scale (one groyne field) can be found in appendix D.2. Unfortunately this level of detail will not be reached during this research.

Main channel

A typical main channel bed morphology of a river with groynes is shown in figure 2.9. A repeating pattern of an oblique scour hole near the tip of every groyne can be seen, followed by deposition in the subsequent area. These deposition areas are called groyne flames. Although it is a repeating pattern still differences can be seen at each groyne. These differences occur due to a random component in the behaviour of eddies. Some groynes have two groyne flames in different directions due to dynamic eddies. As time proceeds they evolve into a single groyne flame (Yossef, 2005).

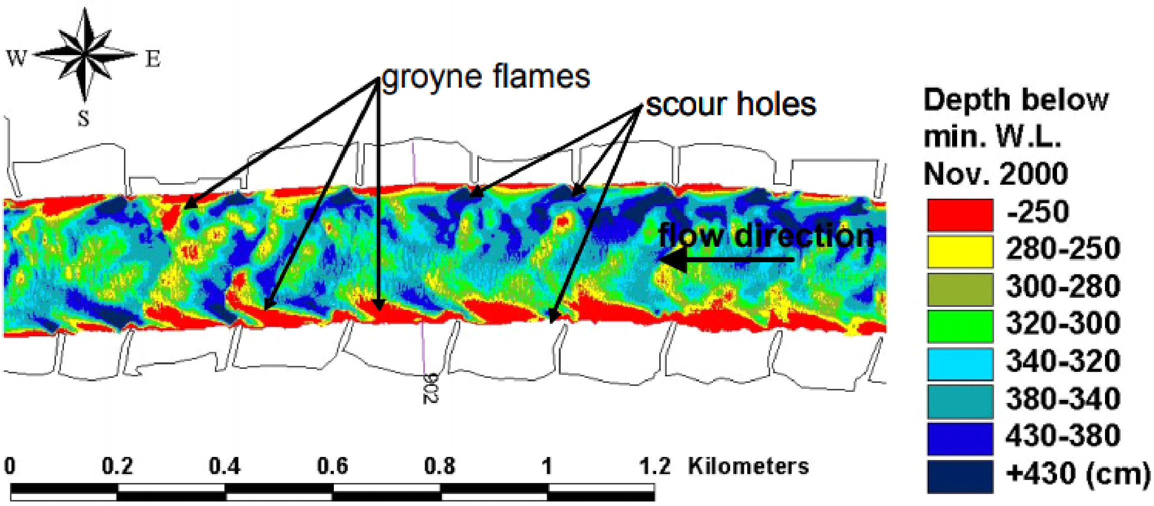


Figure 2.9: Groyne flames and scour holes (Yossef et al., 2006)

The depth and the alignment of the scour hole depend on the water level. The maximum scour depth decreases when the submergence level increases. The alignment of a scour hole rotates towards the river bank as the submergence level increases.

In general, the scour holes in case of emerged groynes are deeper in comparison to the scour holes in the case of submerged groynes.

In table 2.1 the driving mechanisms and the spatial scales of the different morphological pattern features are given.

Table 2.1: Spatial scale and driving mechanism of morphological pattern features (Yossef et al., 2006)

	Spatial scale	**Driving mechanism**
Scour holes	Meters	Increasing turbulence intensity near the groyne head and the formation of three-dimensional vortices
Groyne flames	Tens of meters	Large-scale horizontal eddies
Streamwise bed level undulation	Maximum of the distance between groynes	Acceleration and deceleration of the flow because of streamline convergence/divergence

Emerged groynes

For groyne fields between two emerged groynes sediment import will occur in the downstream part of the groyne field by the primary eddy, advective transport. The sediment settles down while circulating and this induces a deposition region in the downstream region of the groyne field.

In figure 2.10 the bed level of a groyne field can be seen for emerged groynes. The sediment of the deposition region comes from the main channel and not from the scour hole, because the timescale of the development of a scour hole is larger than the development of a deposition region.

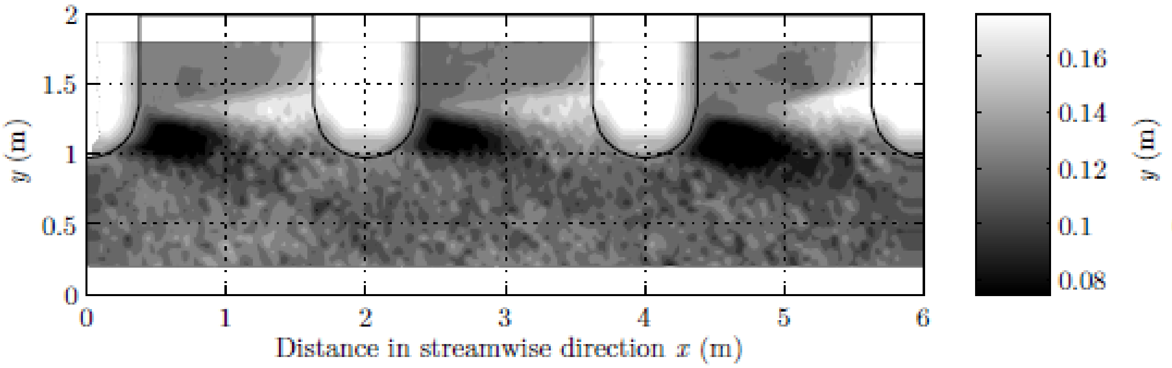


Figure 2.10: Bed level in case of emerged groynes (Yossef, 2005)

Submerged groynes

For groyne fields between two submerged groynes, the sediment import from the main channel to the groyne field is not purely advective, since the main channel flow is not directed to the groyne field. Sediment transport is induced by diffusive and residual advective transport (Yossef, 2005).

Advective transport is caused by a high turbulence intensity in the vertical mixing layer relative to the main channel, which induces high sediment concentrations in the mixing layer and significant sediment exchange. The imported sediment aggrade across the normal line of the groyne, except for the part at the groyne head.

The uni-directional flow over the groynes causes diffusive transport. The net transport of sediment into the groyne fields by diffusive transport is low, because in a series of groyne fields the same amount of sediments is transported over each groyne.

In figure 2.11 the bed level of a groyne field can be seen for submerged groynes. The time scale for deposition is longer than the time scale for erosion. This indicates that sediment from the scour hole is not aggraded in the deposition region.

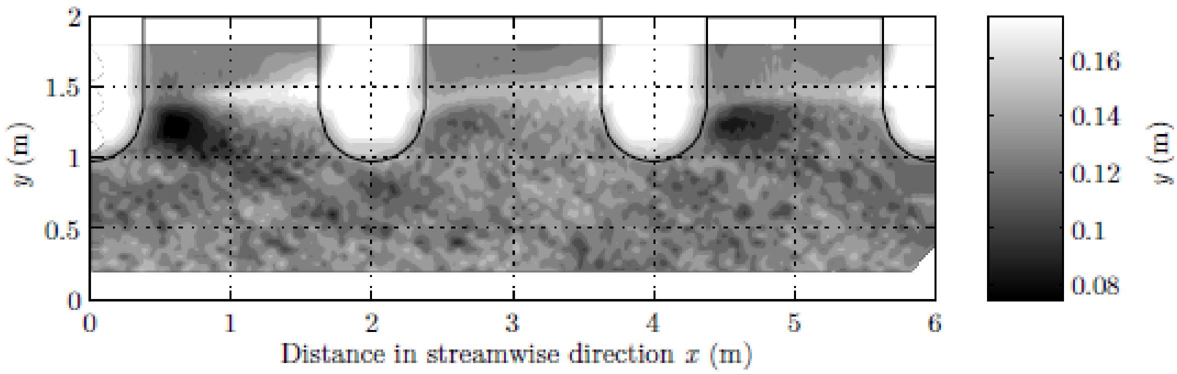


Figure 2.11: Bed level in case of submerged groynes (Yossef, 2005)

The relative contribution between advective and diffusive transport depends on the submergence rate of the groynes. With increasing submergence (water level (h)/level top groyne (hg) ratio gets larger), the velocity in the groyne fields increases. This causes an increase of the velocity gradient over the groynes and a decrease of the turbulence intensity in the vertical mixing layer: the contribution of the diffusive transport increases and the contribution of the advective transport decreases.

In figure 2.12 the line of 50% distinguishes between the range of dominant advective transport and dominant diffusive transport. At low submergence levels, when the h/hg is smaller than 2, advection is dominant over diffusion. The contour lines are almost parallel to the horizontal axis, this means that the discharge plays a minor role in the relative contribution of advection and diffusion.

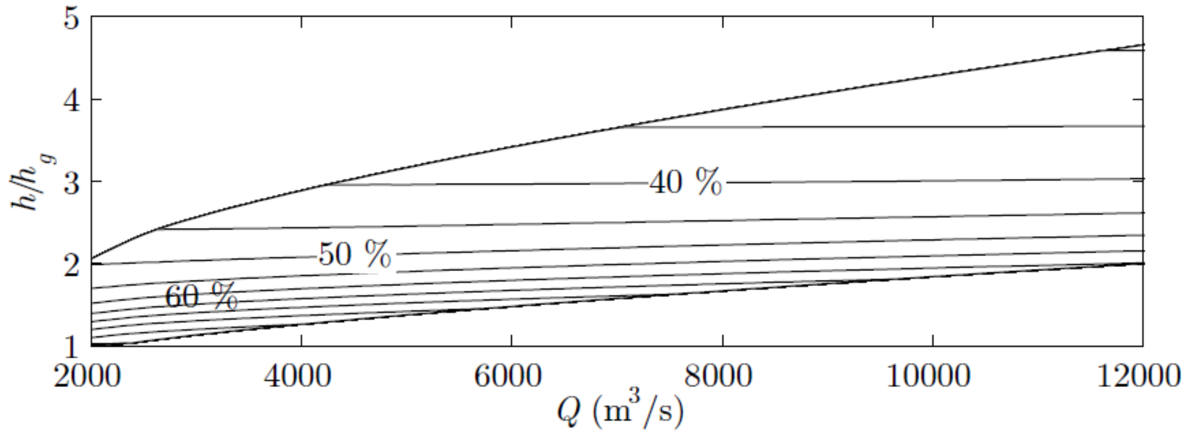


Figure 2.12: Relative contribution of advective transport to the total sediment influx to the groyne fields (Yossef, 2005)

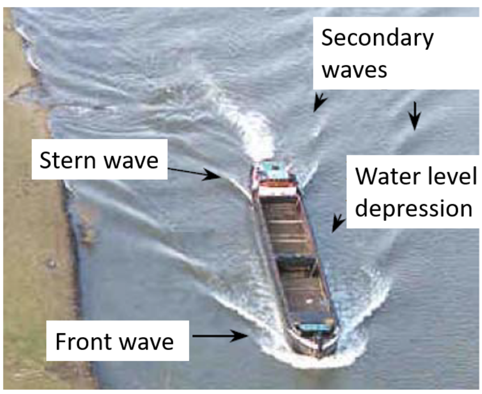
2.3 Navigation

In this section the effect of navigation on the hydrodynamics and the morphodynamics in a groyne field is determined.

In appendix E general wave hydrodynamics (wave parameters and characteristics, wave direction, wave shape, wave breaking, dynamic pressure, wave-induced set-up and wave-induced currents) and in appendix F general wave morphodynamics are briefly explained. The definitions related to these general hydro- and morphodynamics are considered to be known in the following and will be used to explain the wave hydrodynamics and morphodynamics in a groyne field.

Hydrodynamics

The hydrodynamics induced by navigation can be split up into two components: waves and currents. In figure 2.13 an overview of the ship waves and the currents is given. In the following these components will be elaborated in detail. Besides these waves and currents components also suction is an important aspect of a passing ship along a groyne field, lastly this is explained.



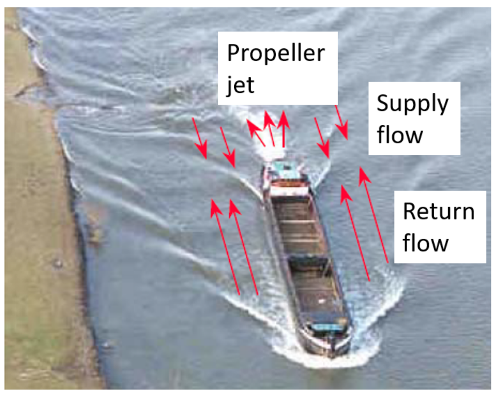


Figure 2.13: Ship waves (left) and ship induced currents (right) (Ten Brinke, 2003)

In figure 2.14 the water level pattern during the passage of a ship at a point close to the river bank (for a river without groynes) is shown. It can be seen that ship waves can be divided into the primary wave system and the secondary wave system.

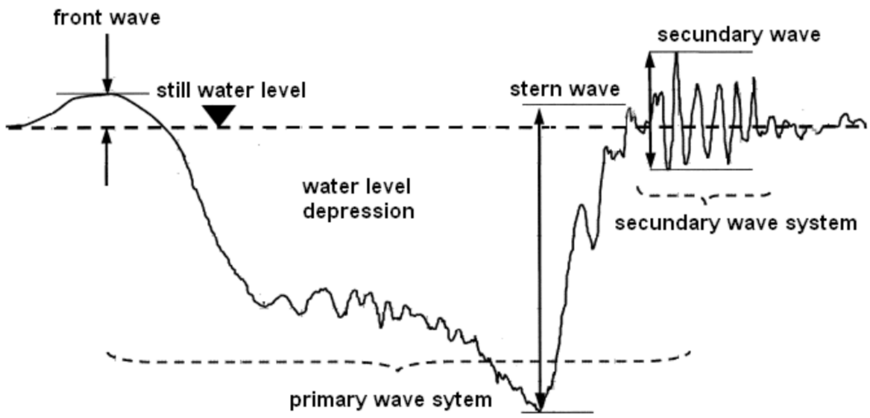


Figure 2.14: Parameters of the ship wave pattern (Roo & Troch, 2010)

The waves in both systems behave like coastal waves, therefore the same relations for example for wave length and wave celerity are valid (Schiereck & Verhagen, 2016).

Primary wave system

A primary wave, a single forced wave, is induced by the draw down: the water level depression between the front wave and the stern wave. Due to the water level depression two currents are induced: the return current and the supply current. The return current transports the water from the bow, along the ship, to the stern to fill up the water level depression. The supply flow fills up the water level depression from the higher water level behind the ship (Ten Brinke, 2003). The primary wave system consists of the primary wave, the return current and the supply current.

The maximum return currents appear close to the barges near the stern. As the ship sails upstream, return currents cause a temporary increase in ambient current velocities. As the ship sails downstream, the return current causes a decrease in ambient current velocities. During low flow conditions the return current may create temporary reversal of the ambient flow (Yossef, 2005).

A primary wave is a negative solitary wave. The river bank is loaded by the primary wave system in two ways: the return flow and the stern wave. The stern wave impacts the river bank more than the return flow (Schiereck & Verhagen, 2016).

Primary waves can be short or long, depending on the depth-length relation. Primary waves have a wave length of about the ship's length. The wave height and the wave period of the primary waves are influenced by ship type, the sailing speed and the cross section of the river. Often a primary wave damps quickly so it should only be considered during a passage of a ship (AnteaGroup, 2019).

Secondary wave system

The secondary wave system is formed by a number of periodic waves, a wave train (Yossef, 2005). Secondary waves are caused by the pressure pattern due to the discontinuities in the hull profile located at the bow and at the stern of the ship.

The secondary waves developed at the bow can be seen as a succession of travelling disturbances. Each disturbance creates a circular wave, which are enveloped by the diverging waves shown the right panel in figure 2.15. The water movement between the diverging waves act like transverse waves. The transverse waves travel in the same direction and with the same speed as the ship, the diverging waves travel more slowly. This velocity difference between the ship and the diverging waves results in an angle between the waves and the sailing line, this can be seen in left panel in figure 2.15. The diverging waves are dominant over the transverse waves and when they intersect cusps form (RWS/DHL, 1988).

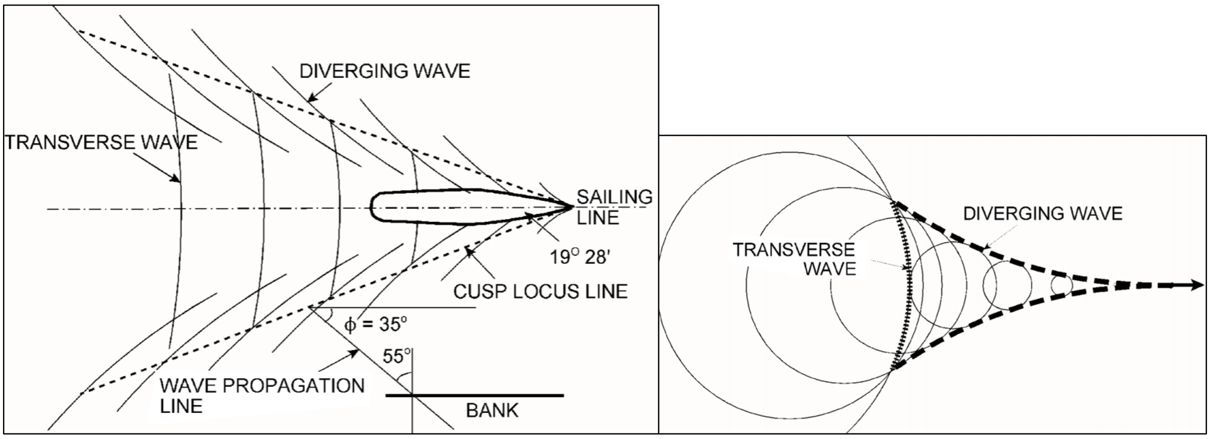


Figure 2.15: Left: Secondary wave pattern; Right: Transverse and diverging waves (Schiereck & Verhagen, 2016)

The wave height is determined by the sailing speed of the ship, the ship type and the cross section of the river. The wavelength and the wave period are determined by the sailing speed (AnteaGroup, 2019). Secondary waves are always short for bulk ships (Schiereck & Verhagen, 2016).

In relatively narrow navigation channels the primary waves are important, because the blockage of the cross-section by ships is not negligible. When blockage does not play a role the secondary waves are dominant (Schiereck & Verhagen, 2016). A secondary wave hardly damps and therefore these waves should be considered even though the ship already passed (Schroevers, Huisman, Van Der Wal, & Terwindt, 2011).

Propeller jet

The currents induced by propeller jets (schroefstraal) are three-dimensional and have a local effect on the main flow and are normally limited to the main channel. Therefore the effect of the propeller jet is little to none in a groyne field.

The hull shape, the characteristics of the propeller, the engine, the dimension of the main channel and the rudder angle determine the potential flow impingement on the bed and river bank (Yossef, 2005).

Suction

The primary wave system induces a current from the river bank to the ship due to the draw down that needs to be filled up: suction. Suction causes that the groyne field will be emptied and it can have velocities of 1.5 to 3 times higher than the velocity of the river current (AnteaGroup, 2019).

The secondary wave system does not induce suction.

Suction depends on the distance between the riverbank and the ship, the width of the ship, the draught of the ship, the frequency of passing ships, the sailing direction, the channel width and the length of the groyne field (AnteaGroup, 2019).

Wave propagation

The secondary wave system, the series of regular waves that are generated by the ship, will move away from the ship as explained in the previous. This is called a wave group.

In deep water the wave crests in this wave group move faster than the wave energy. The wave energy speed is called group speed and the wave crest speed is called the phase velocity. The phase velocity is larger than the group speed which means that the wave crest moves forward from the back to the leading-edge of the group. Furthermore different components of a wave group can travel at different speeds, this is called dispersion. For example longer waves propagate faster than shorter waves.

Ship waves propagate from deep into intermediate and shallow water depths. Wave transformation occurs, because the waves are affected by the riverbed when the water depth becomes less than about half of the wavelength. During wave transformation the wave height, wave length and the direction changes until the wave breaks and loses energy.

The effect of travelling from deep water to shallow water is as follows: The first wave in a wave train is slowed down due to decreasing water depth, the following wave is still at slightly deeper water and is thus moving at a higher speed. This wave tends to ”catch up” with the wave in front which is being slowed. This results in a concentration of wave energy and an increase of wave height, this is called shoaling. The wave height increase by shoaling is limited by energy dissipation due to wave breaking.

Ship passage

The passage of a ship is cut up in phases to show the effect of the ship passage on the flow velocity and the water level in the centre of a groyne field. In figure 2.16 the effect of the passage of a ship along a groyne field on the water movement in the groyne field is given for a ship travelling downstream along the north side of the Waal river during low flow conditions. The largest effect of ship induced water motion can be observed during low water.

These measurements are done near Druten in 1996 for a groyne field with a length of 210 m; a groyne orientation of about 187 degrees North; a discharge of about 1500 - 2000 m^3/s at Lobith. Furthermore the ship is a pushed convoy with 4 barges and has a length of 180 m and a width of 22.8 m.

These measurements can only be used as an indication for what flow velocities and water levels may occur and especially how these fluctuate during the passage of a ship. This is because:

- The specification (flow conditions, geometry etc) of the measured data will not exactly be the same as the specification for this research;
- Not all the parameters of the measurements are known (e.g. the distance of the ship to the river bank and the sailing speed);
- The measurements are done over 20 years ago;

In figure 2.16 a primary and a secondary eddy are present in the groyne field. It can be seen that the passage of a ship induces a small increase of the water level, the front wave, followed by a strong decrease of the water level, the groyne field is emptied. Thereafter the water level increases again, again filling up the groyne field by the stern wave, and a series of secondary waves come in. The strong water level decrease and the secondary waves are clearly visible on the groyne field beach, the water level increase due to the front wave is barely visible (Ten Brinke, 2003).

In appendix G.1 the same phases and data of the water movement are given for a ship sailing upstream along the south side of the Waal and for a small groyne with only a primary eddy. Higher flow velocities in the groyne field occur when the ship sails upstream.

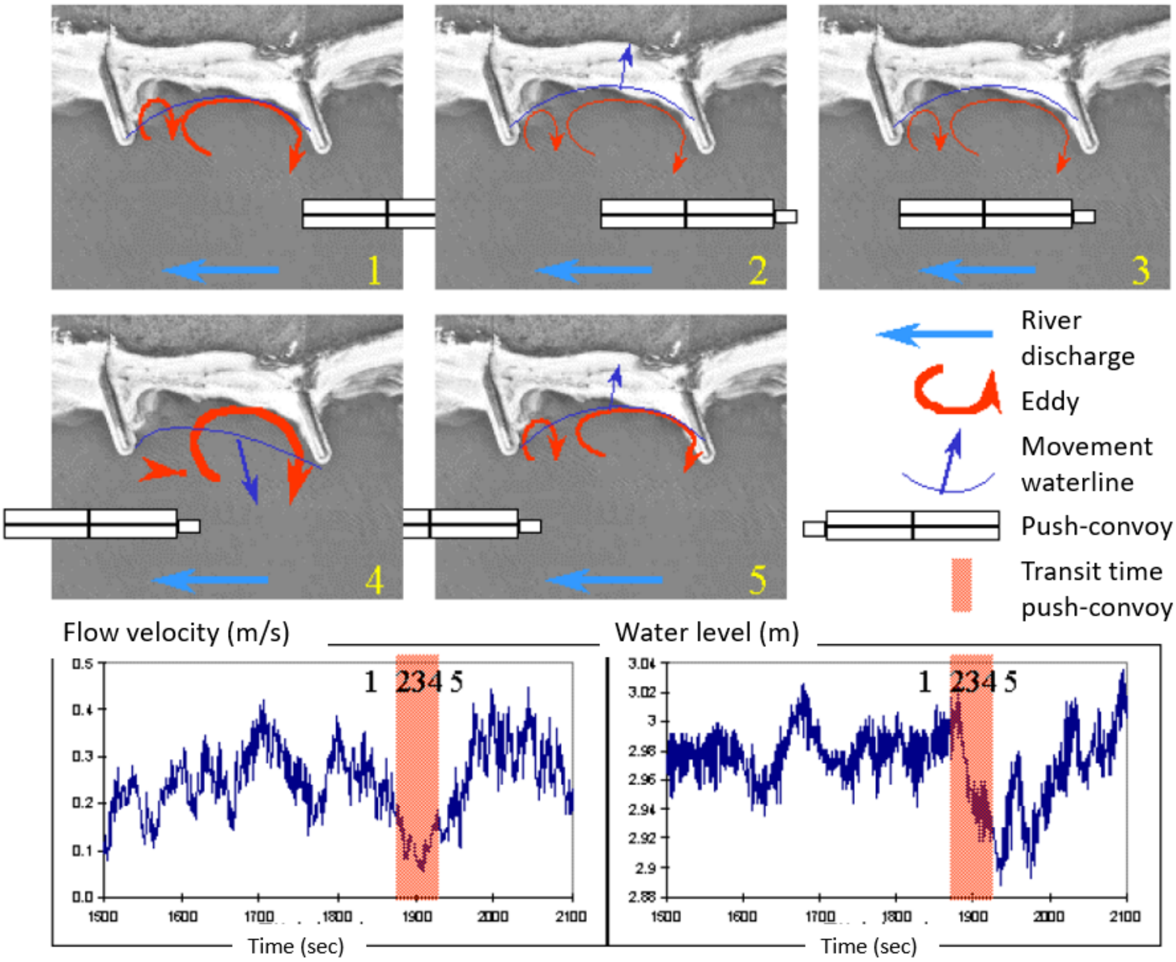


Figure 2.16: Water movement in a groyne field during the passage of a ship (Ten Brinke, 2003)

In the previous the water level and flow velocities during the passage of a ship were given in the centre of the groyne field. In the next part the flow pattern and the flow decelerations and accelerations will be discussed with reference to the same phases.

These phases are illustrated in figure 2.17, two phases are added: the start situation, phase 0 and the end situation, phase 6. The left column gives flow acceleration (red) and deceleration (green) and the right column gives the corresponding flow directions.

Phase 0: The start situation, before the ship passes the groyne field, the current pattern in the groyne field consists of a primary and a secondary eddy. The currents are weak.

Phase 1: The bow of the ship passes a the groyne head, the incoming front wave and the corresponding return current empties the groyne field.

Phase 2: The secondary eddy, in the downstream part of the groyne field, disappears and the primary eddy reduces. Due to the return current a vortex arises downstream of the groyne head, between the ship and the groyne.

Phase 3: When the stern of the ship passes the first groyne, the return current stops and the supply flow begins, so the flow direction reverses. This current fills up again the groyne field.

Phase 4:When the stern of the ship is passing the second groyne, the supply flow is forced to stream from the groyne field to the river axis. There the supply flow meets the return current, which flows in the opposite direction. This reinforces the formed eddy downstream of the second groyne.

Phase 5: When the stern of the ship has passed the second groyne, the supply flow is noticeable in the following groyne field.

Phase 6: Phase 0 is reached again.

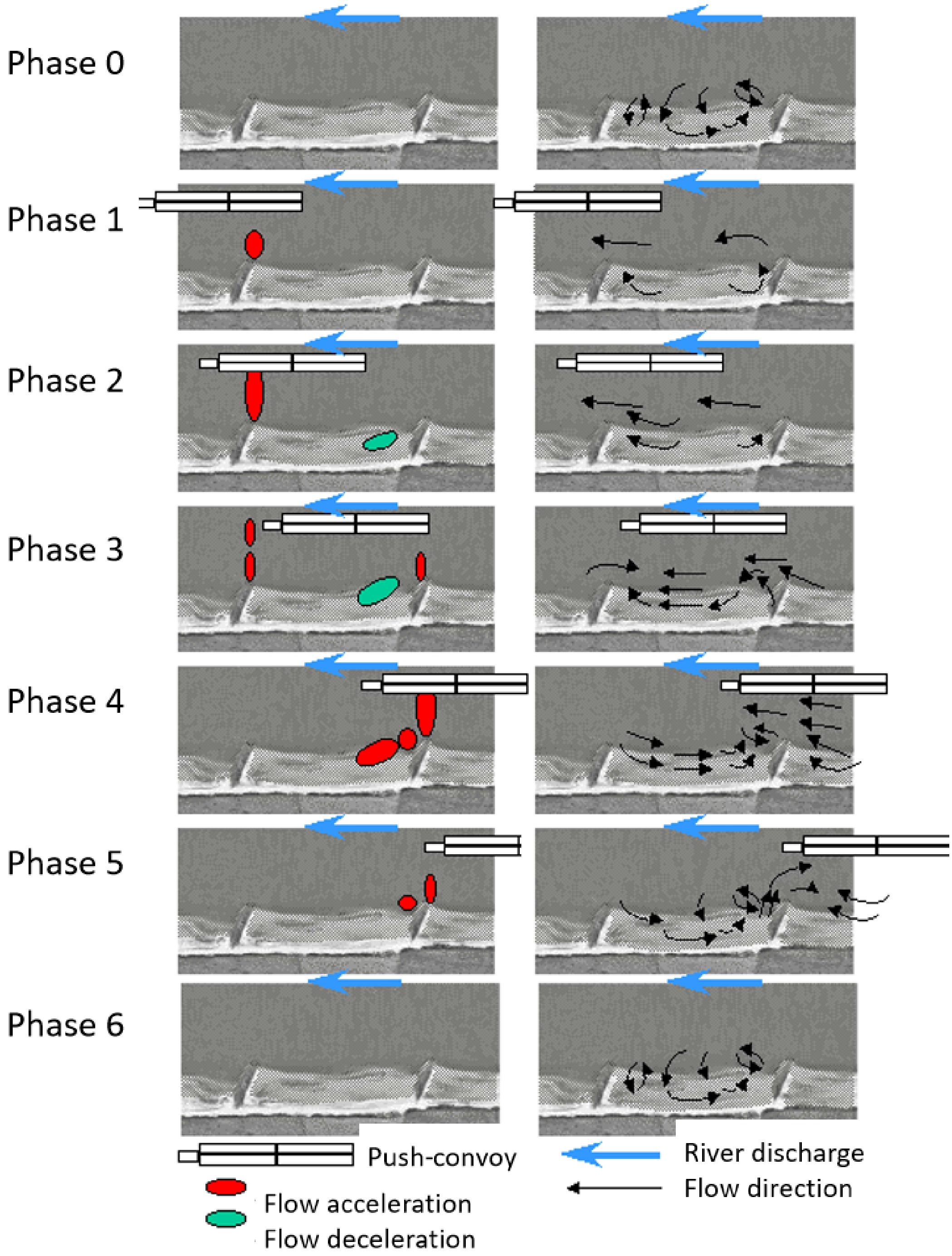


Figure 2.17: Water movement induced by ships (Ten Brinke, 2003)

The strongest current appears downstream of a groyne during the passage of the stern of a ship (Ten Brinke, 2003).

When the dimensions and the draught of a ship increase, the flow velocities of the return and the supply flow will also increase, and therefore the flow velocities, mainly downstream of the groyne, will increase.

The horizontal flow velocities increase almost linearly with the increase of the relative sailing speed. Also the passing distance of a ship has influence on the velocities of the currents. When the passing distance decreases the flow velocities increases between the ship and the head of the groyne.

When the river discharge increases the effects of navigation will get less: due to the discharge increase the river cross section increases, which reduces the return and the supply current when a ship passes. The navigation induced flow velocities will decrease. Furthermore the relative draught decreases, which has a positive effect on the blockage factor. The current blockage factor is introduced to account for the presence of a ship in a current flow field (Chakrabarti, 2005).

Morphodynamics

The navigation induced water motion (waves and currents) influence the morphology in a groyne field by bringing sediment in motion and in transportation. In the following the sediment movement during the passage of a ship along a groyne field is discussed.

Very little data and literature is available on bed shear stresses, sediment concentrations and sediment transport in a groyne field during the passage of a ship. In the following some data is given, these data are measured along the south-side of the Waal near Druten. So for other locations or other ship types, these data may only be used as indication for the order of magnitude of the shear stress and sediment concentrations (Ten Brinke, 2003).

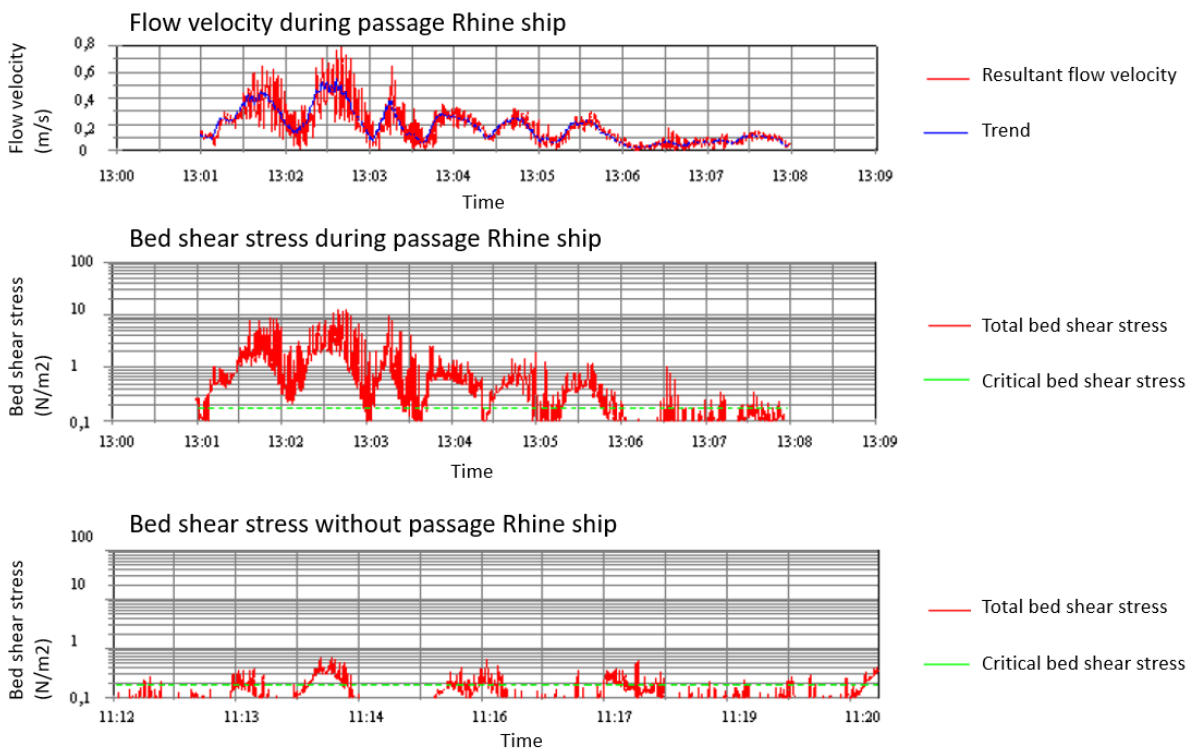


Figure 2.18: Top: flow velocity; middle: bed shear stress; bottom: bed shear stress without passage of a ship (Ten Brinke, 2003)

In figure 2.18 the flow velocities and the bed shear stresses in the groyne field during the passage of a Rhine ship (length = 86 - 110 m; width = 12 m) are given. In the bottom panel the bed shear stresses in the groyne field are given when no ship is passing. The bed shear stress trend seems to follow the flow velocity trend during the passage of a ship. The high flow velocities (suction) and secondary waves induced by the passage of a ship lead to an increase of the bed shear stresses, such that sand will get in motion (initiation of motion).

Especially the flow velocities at the outflow point are high. At the outflow points high sediment concentrations are measured in comparison to the sediment concentrations measured in the groyne field.

In figure 2.19 the contributions of suction and secondary waves resulting from a passing ship to the bed shear stress of the water movement on the sediment of the groyne field beaches for a total of 29 ship passages can be seen. In the top panel (A) the contribution of the bed shear stress close to the river is shown and for the bottom panel the bed shear stress contribution close to the river bank can be seen. It is clear that suction (blue) makes a greater contribution to the total bed shear stress than secondary waves (red).

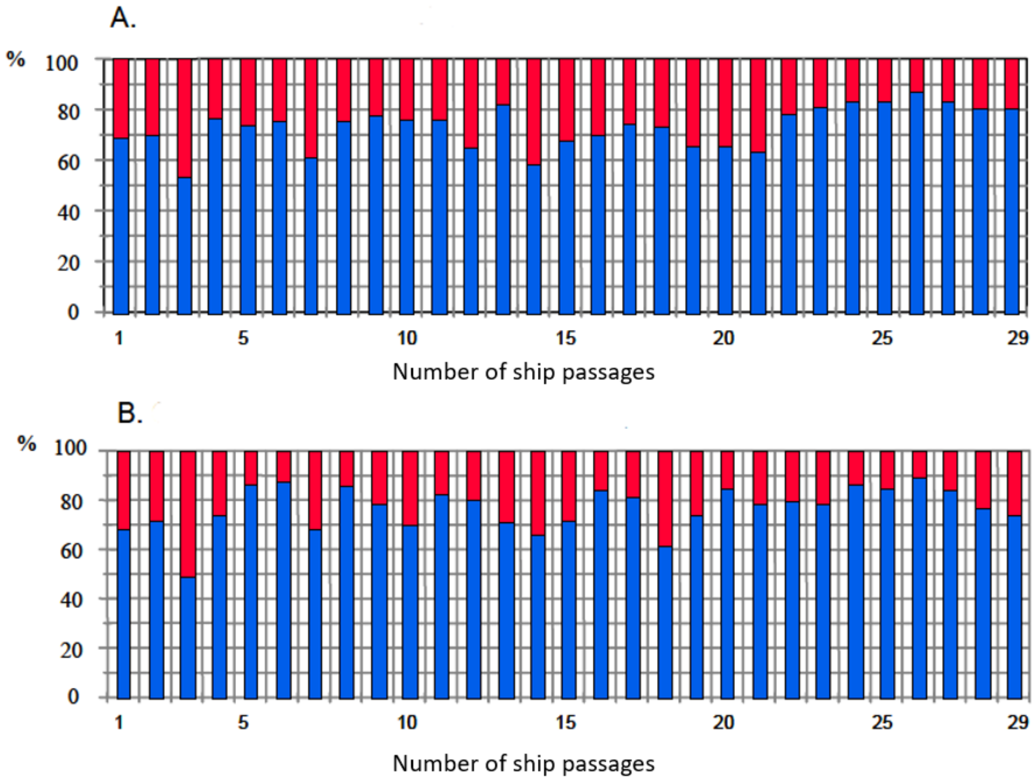


Figure 2.19: Contribution of suction (blue) and secondary waves (red) to the total bed shear stress at A: river side of groyne field; B: river bank side of groyne field (Ten Brinke, 2003)

The passage of a ship leads to the suspension of sediment and keeping the sediment in suspension until long after the ship passed the groyne field. The horizontal large-scale eddies caused by the river discharge transports the eroded sediment to the outflow points of the groyne field to the river.

When two ships passing the groyne field right after each other and the sediment is still in suspension due to the first ship, the second ship will cause more sediment to be suspended and finally transported out of the groyne field by the eddies (Ten Brinke, 2003).

2.4 Evaluation

This literature study is done regarding the predominant hydrodynamic processes and their morphological effects in a groyne field. The main processes are schematised in figure 2.20.

In case of submerged groynes the effect of navigation on the hydrodynamics and morphodynamics in a groyne field is minor, therefore during higher flow conditions navigation is not seen as a main process. In general, the higher the flow conditions the less the effect of navigation.

For the purpose of researching how groyne field nourishments can act as small feeder nourishments that release sediment slowly to the main channel, the hydrodynamic processes in the pink marked cells need to be considered in the remainder of this research. It is important that the base case, set-up in chapter 4, is able to simulate these hydrodynamic processes. For a more complete representation of the behaviour of the nourishment also the sediment interaction between the groyne field and the flood plain should be taken into account, the hydrodynamic process that is not pink marked. This research aspect is not covered by the concerning research due to time limitations.

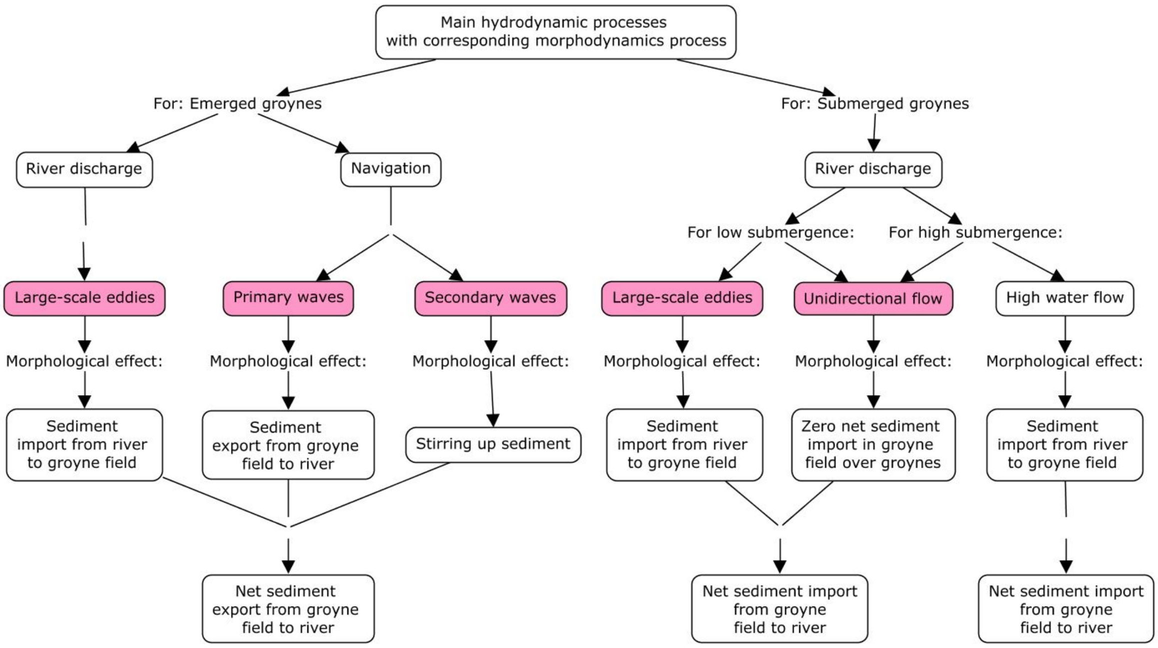


Figure 2.20: Hydrodynamic and morphodynamic processes

3. Additional processes in case of nourishment

In chapter 2 the main hydrodynamic processes and their morphological effect that play a role in groyne fields along the Waal are described. Next, in this chapter other hydrodynamic and morphodynamic processes that probably will be induced by the placement of a nourishment in a groyne field will be looked at. Since little to none in-depth research regarding the behaviour of a nourishment in a groyne field is done earlier, possible analogies with coastal processes and river processes are searched for. These analogies will help to get a supported indication of the hydrodynamic and morphodynamic response in a groyne field to the nourishment.

Analogies with coastal processes are looked for, because, among others, the groyne field beaches have more or less the same bottom profile as wide coastal beaches. Furthermore ship waves act in the same way as coastal waves and lastly the bottom material in the groyne fields along the Waal is sandy.

In the following the processes that could be relevant are elaborated. For every process first the coastal/river context is explained, thereafter the link that could be made to the groyne field with nourishment will be discussed.

3.1 Dune erosion / Sand bar erosion

In this section the possible analogy between dune erosion and erosion of the nourishment in the groyne field is elaborated.

The cross-shore profile of a beach reacts to the hydrodynamic conditions of the sea, which leads to a seasonal behaviour of the beach profile. Seasonal behaviour occurs due to the hydrodynamic conditions (waves, water level, currents) a cross-shore profile is exposed to. These conditions are never constant and vary rapidly such that a stable equilibrium is never reached. The cross-shore profiles are oscillating in response to the varying forcing, but the oscillations are within a steady envelope. The mean position of a profile is defined as a dynamic equilibrium.

In figure 3.1 the summer and winter coastal cross-shore profile are given. In the winter, dune erosion may occur during storms, because the dunes are loaded by waves and currents. These storms lead to the undermining and destabilisation of the dune top. The dune material will break loose and fall on the beach, an avalanche-like process. The eroded sand is moved offshore shaped like a sand bar. In appendix F the sediment transport by waves is explained. The presence and position of these sand bars influence the energy dissipation and therefore the coastal profile response: when the bars are offshore the wave will break further offshore due to the reduced depth and therefore the waves do not impact the dunes anymore. Milder summer conditions will move the offshore winter bars onshore and rebuild the wider berm, the summer profile. Dune erosion along coastal beaches occur during storm conditions. In the Netherlands these storm conditions correspond to an offshore water level of about 5 - 6 m above mean sea level and waves have a wave height of 7 - 9 m and peak periods of 12 - 18 s. The design rule in the Netherlands allow for erosion rates of 80 - 100 m dune retreat during storm conditions (Bosboom & Stive, 2015).

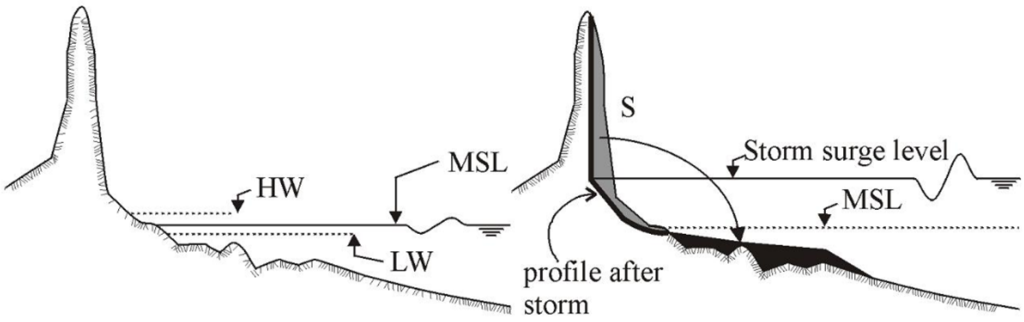


Figure 3.1: Left: summer profile, Right: winter profile (Bosboom & Stive, 2015)

These hydrodynamic conditions are not likely to happen in a groyne field along a river: the water depth in a groyne field during high water is limited by the height of the river bank, because the water will flow into the flood plains. Because the water depth in a groyne field is limited also the wave height is limited, since the following relation for the significant wave height of irregular waves travelling into shallow zones can be used as indication:

$$H_s > 0.3 * h$$

But it may be expected that the same principles of dune erosion due to the attack of waves and currents apply to a nourishment when it is attacked by ship waves and ship induced currents. Furthermore the avalanching principle probably occurs when the nourishment is just placed and the sides of the nourishment are steep slopes. In summary: based on coastal dune erosion it may be expected that the nourishment just after placing will erode by avalanching, thereafter the nourishment will erode along the sides due to the attack of ship induced water movement (waves and currents).

Next to the dune erosion processes also the sand bar movement along a coastal cross-shore profile is highlighted in the above. This principle may also be applicable to a groyne field nourishment. When the nourishment is placed as a sand bar in the groyne field it may be moved onshore (directed to the river bank) during less energetic “summer conditions” and moved offshore (directed to the main channel) during more energetic “winter conditions”. In coastal area’s summer conditions correspond to a calm period with normal water level and wave conditions and winter conditions correspond to storm wave heights and surge conditions (Bosboom & Stive, 2015).

During extreme conditions, high and long waves, the sediment transport by undertow is dominant and the sand bar moves offshore. During mild conditions the sediment transport by, among others, short wave skewness is dominant and the sand bar moves onshore. This is further explained in appendix F.

For groyne fields these summer and winter conditions cannot be defined in the same way as for coastal area’s. For example the incoming wave characteristics are, among others, determined by the ship characteristics and these ships travel along the groyne field during the whole year. But it may be said that the nourishment travels onshore, to the river bank, during little to no wave forcing and travels offshore, to the main channel, during the passage of a ship and ship waves forcing occurs in the groyne field.

3.2 River bank erosion

In this section the possible analogy between river bank erosion and erosion of the nourishment in the groyne field is elaborated.

The cross-shore profile of a groyne field beach reacts to the hydrodynamic conditions of the river, this leads to a seasonal behaviour of the beach profile. The principle of this seasonal behaviour is the same as for coastal beaches. During middle and high flow conditions the river bank is loaded by flow velocities along the river bank and by wave loads due to navigation (Duijn, 1996).

During high flow conditions the water level increases and ship waves can reach the river bank and impact it: undermining and destabilisation of the river bank top. The river bank material will break loose and fall along the river bank into the groyne field, an avalanche-like process. Eroded sediment material from the river bank may be transported offshore by the undertow. The combination of an undertow and high concentrations of suspended sediment leads to an large offshore transport capacity. Further away from the river bank the transport capacity of the flow decreases and the sediment will settle. The cross-shore profile of the groyne field is changed and adapted to the flow conditions: a terrace arises in front of the river bank as shown in the left panel of figure 3.2 and the river bank erosion decreases. The terrace ensures that the energy of incoming waves is dissipating more efficiently: ship waves dissipate over the distance as they propagate, so the longer they travel the lower energy they carry. In addition, a terrace reduces the water depth in the groyne field in front of the river bank which creates higher resistance for wave advance than deeper areas, especially if waves refract, diffract and break. Therefore the river bank erosion decreases (Duró et al., 2019).

In highly regulated rivers with high ship traffic where the water level frequently changes, the river bank profile gets steeper and therefore mild terraces are formed along the river bank (Duró et al., 2019).

The quantity of river bank erosion depends on the frequency of passing ship and their characteristics (Duró et al., 2019).

Figure 3.2: Left: River bank erosion in a groyne field along the Waal (Morijn, n.d.), right: River bank erosion Heerewaarden (Stokkermans, 1993)

The flow pattern near the river bank can be three-dimensional, so there is high turbulence intensity. This may be caused by irregularities along the river bank what can cause detaching boundary layers and mixing layers. River bank erosion can occur by these flow pattern, but the contribution of this river bank erosion is small in comparison to the river bank erosion induced by ship waves. So the terrace forming is mostly because of ship waves (Duró et al., 2019).

Trees growing on river banks consisting of highly erodible material do not significantly improve the resistance against flow erosion and ship wave erosion (Duró et al., 2019).

River bank erosion does occur in the Waal, for example at a groyne field at Heerewaarden. In figure 3.3 the depth profile of the formed terrace can be seen on the right and left shows how this river bank erosion looks from above. At the bottom of the satellite photo an edge can be seen, at this edge river bank erosion occurs such as in figure 3.2 in the right panel.

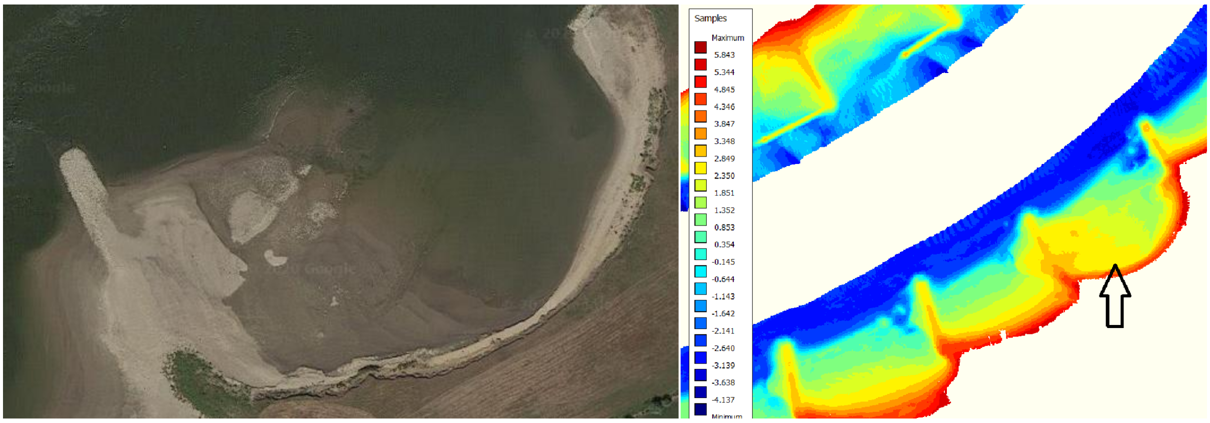


Figure 3.3: Left: satellite photo river bank erosion Heerewaarden, right: depth profile of river bank erosion Heerewaarden

The principle of dune erosion seems to largely correspond to the principle of river bank erosion. So the analogy with the erosion of a groyne field nourishment is more or less the same: it may be expected that the nourishment just after placing will erode by avalanching, thereafter the nourishment will erode along the sides due to the attack of ship induced water movement (waves and currents).

Also the principle of sand bars and terraces seems to largely correspond: wave energy is dissipated before the wave reached the dune/river bank. So it may be expected that when a nourishment is placed in the groyne field waves will break on it and the nourishment material will be eroded and transported.

The movement of coastal sand bars offshore and onshore by varying wave conditions may partly correspond to the movement of the terraces, since the toe level of the terraces is depended on the water level. But the terraces seem not to move as a whole off- and onshore (from and to the riverbank). This difference causes that the proposed analogy between nourishments and sand bar (described in section3.1) on the aspect of movement is not realistic anymore, because terraces are formed in rivers by ship waves and therefore it may be assumed that nourishments that will be placed in a groyne field like sandbars will also not move as a whole.

3.3 Cross-shore currents

In this section the possible analogy between the cross-shore flow pattern around a shallow shoal and a groyne field nourishment is elaborated.

In appendix E.6 wave-induced currents due to wave set-up differences along the coastline are elaborated. These wave-induced currents do occur in the case of shoals.

On shoals the waves are breaking. Due to refraction, the waves will tend to converge toward the top of the shoal. As the waves break on the offshore slope of the shoal, they generate a dissipation related wave force. At the top of the shoal there is no closed boundary requiring a zero mean flow. Instead, the water will flow over the shoal in the direction of the force. The water flows over the shoal until it reaches the channel behind the shoal, where water level gradients will deflect it and drive it to the sides of the shoal. There it has room to flow towards the sea again, thus closing the circulation, shown in figure 3.4.

The flow pattern around a shoal induced by waves in coastal zone possibly can be indicative for the flow pattern induced by ship waves around a nourishment in a groyne field. Since ship waves act the same as coastal waves, wave-induces currents due to set-up differences may appear. The combined effect with the large-scale horizontal eddies in a groyne field during low water probably cause the water to flow in the same direction as the eddy after the water flows over the nourishment instead that the water flow along both sides of the nourishment.

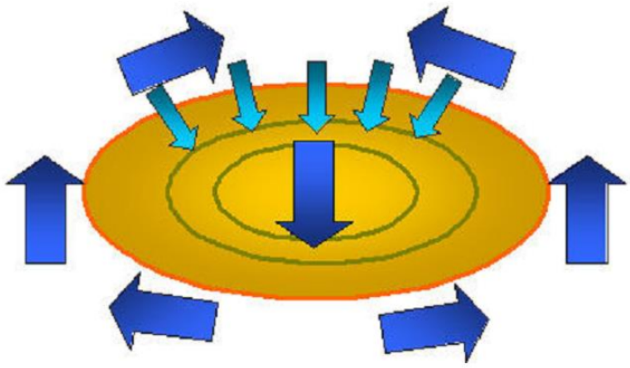


Figure 3.4: Wave-induced forces and currents around a shoal (Bosboom & Stive, 2015)

In case of a series of shoals parallel to the shore line the interruption of wave breaking can generate bathymetrically controlled channel rips. These channel rips are strong, narrow, seaward-flowing currents between the shoals driven by breaking waves. The size and alongshore spacing of channel rips is related to regional wave climate, increasing with increasing wave height, period and energy (Aarninkhof et al., 2020). Rip channels transport sediment offshore in suspension and bed load and the total rip circulation can transport sediment back to the shore, but still a lot of research is needed.

This coastal principle gives an indication that waves may induce strong currents around and over a nourishment and may cause sediment transport. It should be kept in mind that coastal waves are there 24/7 and ship waves only occur when a ship is passing (very often but not 24/7, especially at night traffic is less). Besides the river flow has an effect on the hydrodynamics and the morphodynamics in a groyne field. So it seems unlikely that real rip channels will develop.

Next to the incoming ship waves, ships also cause strong currents in groyne fields while passing: the groyne field is filled up by the front wave, emptied by the suction and filled up again by the stern wave followed by damped fluctuation of the water depth. Filling and emptying of the groyne field cause high flow velocities in the groyne field. When a nourishment is placed in a groyne field, dependent on the location, shape and volume of the nourishment, the water will flow around and/or over it. Due to the contraction of the flow area because of the the nourishment the flow velocity will increase and narrow strong currents may occur. These strong currents may have the same effect on the morphology as the rip currents induced by wave set-up. The generation of rip currents is different, but possibly the effect of rip currents and the strong currents due to flow area contraction on the morphology is the same.

3.4 Alongshore currents

In this section the possible analogy between the long-shore flow pattern around a shoal and a groyne field nourishment is elaborated.

Oblique incident coastal waves cause an alongshore current, this is explained in paragraph E.5. The direction of this alongshore current is parallel to the shoreline and the depth contour lines. Also in the alongshore direction waves cause sediment transport. The role of waves in the alongshore transport is that it brings sediment in suspension and with that waves increase the sediment concentration in the water column, since the wave motion in the breaker zone is nearly perpendicular to the alongshore current. The sediment is brought into suspension by:

- Orbital motion (appendix E.4)
- Wave breaking

Due to wave breaking the turbulence in the water column is increased and therefore suspended sediments are brought into the upper part of the flow. This sediment stirring takes place in a narrow zone just offshore of the breaker line. The suspended sediment is transported by the wave-induced alongshore current in case of oblique incident waves.

When oblique incident waves come in with a relatively small angle with respect to the shore normal (deep water wave angle smaller than 45 degrees) the transport rates increase with increasing wave angle. Therefore a shoreline has a tendency to flatten out bumps and dents until the straight equilibrium coastline is restored, a negative feedback process.

As a result convex depth contours result in erosion and concave depth contours to sedimentation. Convex and concave are defined as seen from the sea. In figure 3.5 the locations of sedimentation and erosion are given in case of a 'bump' and a 'dent'.

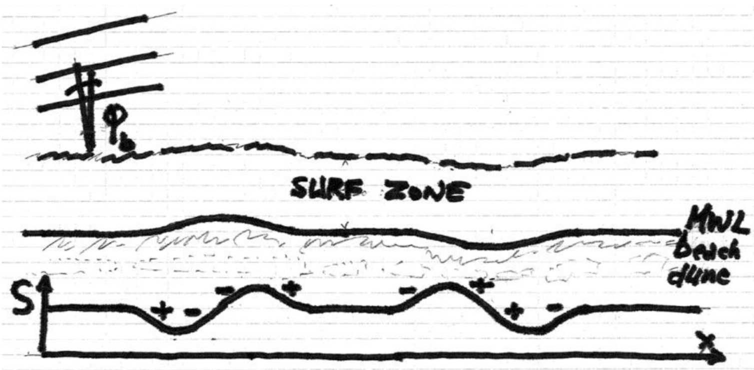


Figure 3.5: Concave and convex depth contours with corresponding erosion (-) or sedimentation (+) (Bosboom & Stive, 2015)

In figure 3.6 the effect of oblique incident waves on a perturbation in the shoreline is given. In panel A the terms and axes are defined, in panel B the transport curve as a function of the relative deep water wave angle is shown. The maximum sediment transport occurs around an angle of 45 degrees. In panel C it can be seen that the shoreline response to low-angle waves by eroding perturbations as explained earlier. In panel D the response of the perturbation to high-angle waves is given. The perturbation will grow, this is a positive feedback process.

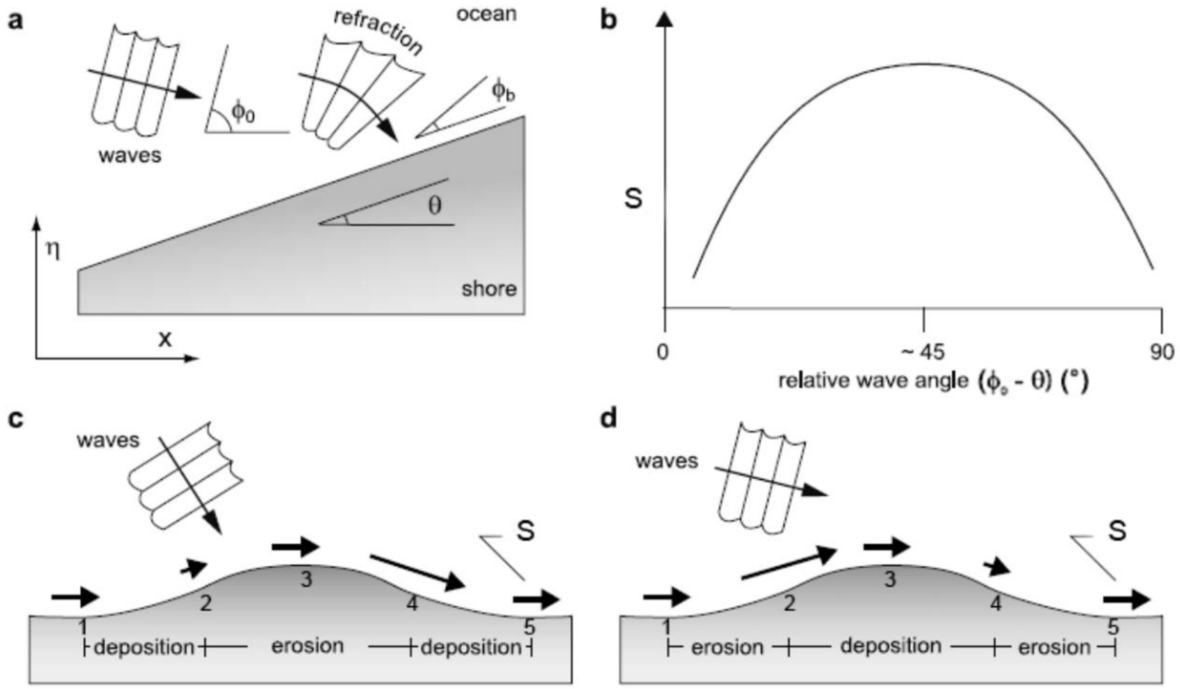


Figure 3.6: Response of a perturbation in the shoreline (Bosboom & Stive, 2015)

The principle of negative feedback of bumps due to alongshore currents because of low-angle oblique incident waves may give an indication what the effect is of oblique incident ship waves on a nourishment in a groyne field. Probably the nourishment will be eroded on the main channel side parallel to the river bank.

3.5 Coastal nourishment

In coastal area's nourishments are applied for different purposes: to compensate for losses as a result of structural erosion; to enhance safety of the hinterland against flooding and to protect the beach and dune area; to broaden a beach or reclaim land. The first purpose corresponds to the purpose of a groyne field nourishment: compensate for structural erosion.

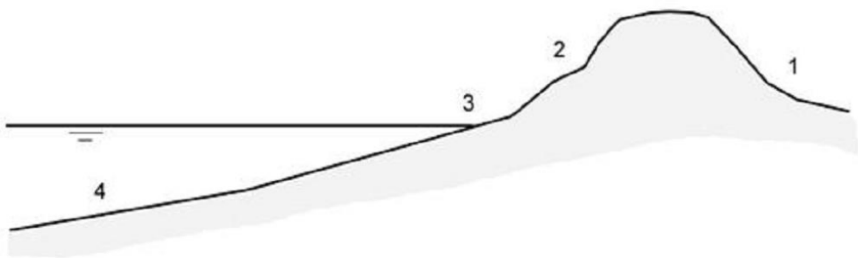


Figure 3.7: Possible nourishment locations (Bosboom & Stive, 2015)

A coastal nourishment can be placed at multiple locations across the coastline, see figure 3.7: on the inner slope of the dune (1); on the outer slope of the dune (2), on the dry beach (3) or on the shore face (4). A coastal nourishment that needs to compensate for structural erosion should be placed in the active zone (2,3,4). When the nourishment is placed within the active zone (2,3,4), the waves will redistribute the material over time. When the nourishment is placed on the shore face or the dry beach (3,4), it can be seen as local perturbation, which will be flattened out by cross-shore transport processes (Bosboom & Stive, 2015).

These locations along the coastal cross-section are also identifiable for the cross-section of a groyne field beach: the inner slope of the river bank (1), the outer slope of the river bank (2), the dry groyne beach (3) and the wet groyne field beach (shore face of the groyne field beach) (4).

Based on the principle that a coastal nourishment, that needs to compensate for structural erosion, should be placed in the active zone and that it can be seen as local perturbation that will be flattened by cross-shore transport processes, for example waves and currents, it is likely that this also holds for a nourishment placed at location 3 or 4 in a groyne field, where these waves and currents are induced by passing ships.

3.6 Evaluation

This literature study is done regarding the possible analogies between coastal/river processes and the processes that may be induced by the nourishment in a groyne field. In figure 3.8 the coastal and river processes are schematised.

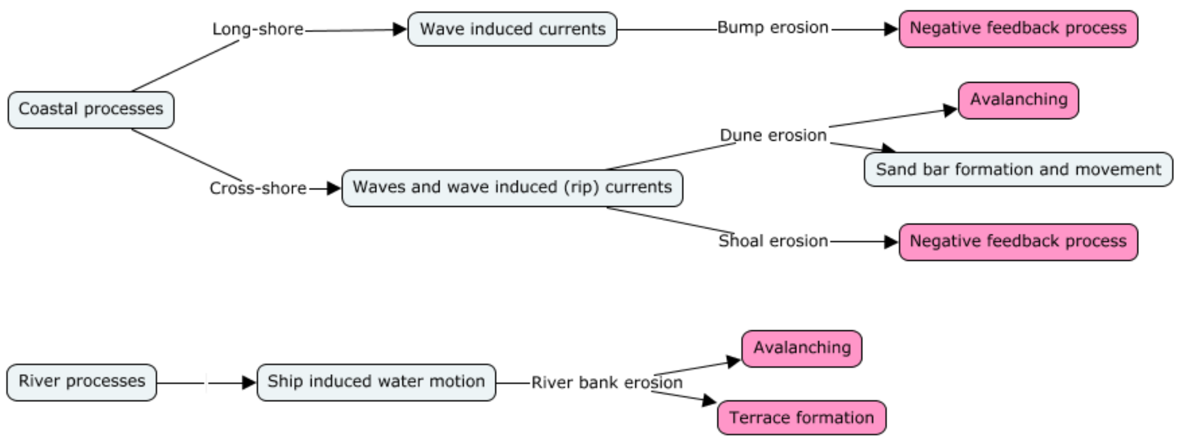


Figure 3.8: Additional processes in case of nourishment

For both the river and coastal processes the hydrodynamic process is given with the morphological effect. The pink morphological processes seem to be the most likely to occur in a groyne field after a nourishment is placed. The sand bar formation and movement of the sand bar onshore or offshore is not marked. This process is, among others, mainly induced by constant wave forcing by or summer or winter conditions. In rivers the water level can be linked to the summer or the winter season but the waves and the wave induced currents due to the passage of ships is not directly linked to the summer or winter season. Furthermore the wave forcing by ships is not constant.

For the purpose to research how groyne field nourishments can act as small feeder nourishments that release sediment slowly to the main channel, the hydrodynamic processes in the pink marked cells needs to be considered in the following of this research. It is important that the base model, set-up in chapter 4, is able to simulate these processes.

4. Numerical model methodology

In this chapter the model set-up, the calibration and the validation of the base model will be described. Thereafter this model will be used to simulate and research the hydrodynamic and morphodynamic processes the effects of placing a nourishment in a groyne field. In section 1.3 it was explained that for this research the hydrodynamics, and whenever possible the morphodynamic processes, will be simulated by setting up a computational model. In selecting a model the primary focus is on simulating the hydrodynamic processes, because computational modelling of sediment transport and bottom changes in a groyne field due to both waves and currents is still in development.

In figure 2.20 and in figure 3.8 the processes highlighted in pink are the processes that the simulation software tool should be able to simulate. In the next section two commonly used software tools are elaborated and a choice is made for the tool that will be used for this research.

4.1 Software selection

To select a suitable software tool two commonly used process-based models are compared:

XBeach is a depth averaged shallow water flow model, which is developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts.

Delft3D is 3D modelling software to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments.

In appendix H the model specifications are further elaborated for XBeach and Delft3D.

Based on literature several components of the two models are compared with regard to the following factors: the spatial and time scale, the included cross-shore and alongshore processes and the extend to which a ship passage and ship induced waves can be simulated. Furthermore earlier done research is taken into account in the selection process of a suitable software tool.

Spatial and time scale

In table 4.1 the general applied spatial and time scale used by XBeach and Delft3D are given. For this research a study area of a series of groyne fields along the Waal is chosen. This will have a length of about 2 - 3 km and a width in the order of a 0.5 km, the width of the Waal. The passage of a ship along a groyne field has a duration of minutes, changes in the river discharge have a time scale of days and the expected time scale of the erosion of a nourishment is months.

Table 4.1: Spatial and time scale of XBeach and Delft3D

	Spatial scale	**Time scale**
XBeach	m - km	hours - days
Delft3D	km - 10 km	days - years

Cross-shore processes

Earlier research (Zimmermann et al., 2015) is done about the capability of Delft3D and XBeach to simulate onshore and offshore sediment transport and the behaviour of a sand bar in a coastal area. The results of this research are summarised in table 4.2. The last column probably gives an indication for the relevance of a process for sand bar behaviour along the coast, which could also be an indication for the nourishment behaviour (explained in chapter 3).

A detailed explanation of the information in the table can be found in appendix H.3.

Table 4.2: Cross-shore processes associated with sediment transport simulated in a 2DH model in Delft3D and XBeach and their importance for bar behaviour (Zimmermann et al., 2015)

Process	**Delft3D**	**XBeach**	**Bar behaviour**
Stokes' drift	No	No	-
Return flow	No (hydrodynamics only)	Yes	++
Wave asymmetry	No	Yes (in suspended load)	+
Wave skewness	Yes (in bed load)	Yes (in suspended load)	++
In- and exfiltration	No	No (hydrodynamics only)	–
Gravity	Yes (correction of bed load transport)	Yes (correction of equilibrium concentration)	+
Turbulence	No	No	+
Wind stress	Wind field: Yes Cross-shore recirculation: No	Wind field: Yes Cross-shore recirculation: No	-
Fall velocity	No	No	–
Bed forms	Yes (predictor)	Limited (initial conditions only)	=
Long waves	No	Yes	++
Wave roller	Limited (not convenient)	Yes	+
3D effects	Limited (longshore current and wind only)	Yes	- to ++

Ship waves

Earlier research (Zhou, Roelvink, Verheij, & Ligteringen, 2013) is done about the capability of Delft3D and XBeach to simulate primary and secondary ship waves.

The moving pressure field method is used to reproduce ship induced water movement in Delft3D and XBeach. The ship is replaced by a pressure field and the movement of the ship is simulated by moving this pressure field at each time step corresponding to the ship's sailing speed. The pressure of the ship depends on the draft of the ship. Furthermore the dimensions of the ship are of importance (Zhou et al., 2013).

In figure 4.1 the principle of a moving pressure field that simulates a ship in XBeach is shown.

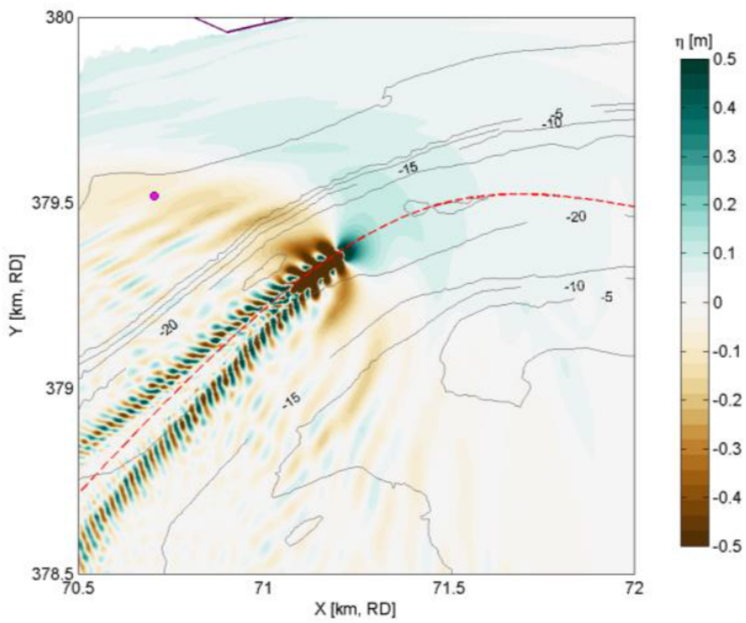


Figure 4.1: Ship waves situated in the Scheldt Estuary (The Netherlands) simulated with XBeach (The XBeach Team, n.d.)

Several validation tests on passing ships are already performed in Delft3D-FLOW and XBeach in the research of Zhou et al. From these tests it was concluded that Delft3D cannot handle high frequency secondary waves with low eddy viscosity value. To obtain a realistic primary long wave, secondary waves have to be damped out by increasing eddy viscosity to a very high value (Zhou et al., 2013).

The non-hydrostatic flow model in XBeach could reproduce the primary wave system as well as secondary (short) wave system (Zhou et al., 2013) if:

$$k * h < 2$$

$$k = (2 * \pi)/\lambda$$

k = wave number (1/m); h = water depth (m); λ = wavelength (m)

Primary waves (front and stern wave) have a wave length of about the ship's length and the wave length of the secondary waves depends on the sailing speed, but for a wave period of 4 s a wave length in the order of multiple 10 m is normal (Byres & Ng, 2011).

Sediment exchange main channel and groyne field

Earlier research (Yossef, 2005) is done about the simulation of sediment exchange between the main channel and groyne field in case of emerged groynes with Delft3D. The flow pattern in a groyne field is predominantly two-dimensional, with mainly horizontal eddies. The horizontal eddies shedding from the tip of a groyne and turbulence close to a groyne with a spatial scale of tens of meters and a time-scale in the order of minutes. In order to simulate the sediment exchange accurately these water movements need to be simulated.

For the research of Yossef a two-dimensional depth-averaged model is used, taking an eddy-resolving approach, this is called HLES (horizontal large eddy simulation). In figure 4.2 the conventional procedure and the eddy resolving procedure followed to update the bed are given (Yossef, 2005).

The hydrodynamics in the main channel and the groyne field simulated by Delft3D-FLOW coupled with HLES were represented accurately, but the morphodynamics of the groyne field cannot be simulated accurately by Delft3D-MOR coupled with HLES.

The morphodynamics in the main channel were realistic, but the morphodynamic activity within the groyne field was largely under-predicted. This is a problem when researching the sediment exchange between the main channel and the groyne field.

The morphodynamics in groyne fields cannot be reproduced accurately by Delft3D-MOR coupled with HLES due to the lack of a transport model that accounts for the increased turbulence level in the mixing layer, vertical motions in picking up sediment and keeping it in suspension for extended distances (Yossef, 2005).

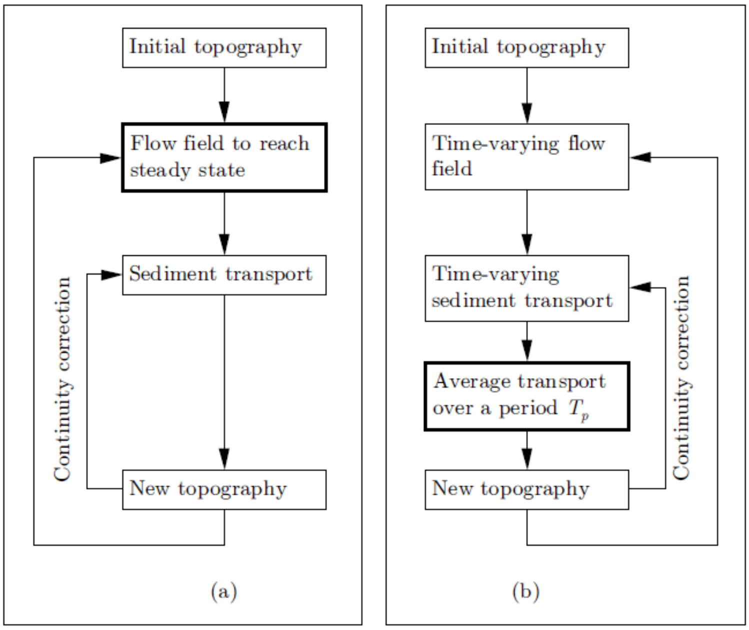


Figure 4.2: Left: Flow chart conventional morphological calculation; Right: Flow chart eddy resolving calculation

Software choice

The information from the researches done earlier gives for several modelling aspects an indication which software tool (Delft3D and XBeach) should perform better for the objective of this research. For Delft3D and XBeach a summery is given of the elaborated modelling aspects and the extent to which the software tool is capable of handling these aspects. In table 4.3. + means capable, ++ means very capable, - means less capable and ? means that it is not known.

Table 4.3: Software capabilities

	Delft3D	**XBeach**
Spatial and time scale	+	+
Cross-shore processes	+	++
Primary ship waves	++	++
Secondary ship waves	-	+
Sediment exchange main channel and groyne field	-	?

Considering the pros and cons XBeach will be used in this research. The capacity of XBeach to simulate ship waves was decisive in this, since from chapter 2 and 3 appeared that navigation is an important factor for the morphodynamics in a groyne field. A coupling between Delft3D and XBeach is also considered, but due to the time limitation of this research this was not an option.

4.2 Model set-up

In this section the aspects of setting up a XBeach model and the choices and assumptions that come with it are elaborated.

Area/Domain

First a research location is selected along the Waal. The Waal river is chosen because of:

- Bed degradation;
- Intensive navigation;
- Sandy groyne fields;

But also Rijkswaterstaat already looked at the possibilities of applying groyne field nourishments along the Waal.

The geography of the Waal, the findings of a preliminary research of Rijkswaterstaat and the available data are considered when selecting the research location.

To pick a research location a couple of selection criteria are set-up. In the following this criteria are summed up with an explanation:

1. Located at a relative straight river section to exclude bend effects;
2. Located between Tiel and Nijmegen (Between Rhine km 880 and 915) such that there is sufficient sediment transport capacity for transporting gravel and coarse sand;
3. Data available at the location to be able to build and to validate the model;
4. Series of groynes (at least 5 groyne fields) in a straight line to account for extra needed domain for the boundary condition effects to damp out;
5. Series of groynes with regular groyne(field) characteristics, typical for the Waal, to make it easier to see and find patterns in certain hydrodynamic and morphodynamic processes;
6. Series of groynes that are representative for typical groynes along the Waal between Tiel and Nijmegen;
7. At or close to a proposed location of Rijkswaterstaat to take their preliminary research into account;

The research location should meet all criteria. To elaborate further on selection criterion 2: bottom level measurements of the Waal (main channel and groyne fields) are available, provided by Rijkswaterstaat. In the appendix I a description of these data sets is presented. Furthermore registrations of passing ships along the Waal are available. This data is owned by Frank Collas and cannot be made public.

Further elaborating on selection criterion 5: the different groyne(field) characteristics are presented in table 4.4 together with the parameter values for groynes along the Waal. The definition of the characteristics are shown in figure 4.3.

Table 4.4: Characteristics of groynes along the Waal (Yossef, 2005)

Parameter	**Mean**	**Min**	**Max**	**Standard deviation**
S: spacing between groynes (m)	198.2	50	420	37.7
L: groyne length (m)	67.9	0	175	28.6
L_of,w: length along the waterline (m)	215.1	100	480	43.5
Y_th: distance normal to thalweg (m)	129.8	10	320	93.6
B_mc: main channel width (m)	279.5	252	412	35.2
G: orientation of a groyne (deg)	-8.0	-30	10	8.7
D_50: bed material (μm)	439.5	200	1300	264.5
Beach slope (-)	0.042	0.03	0.05	0.008

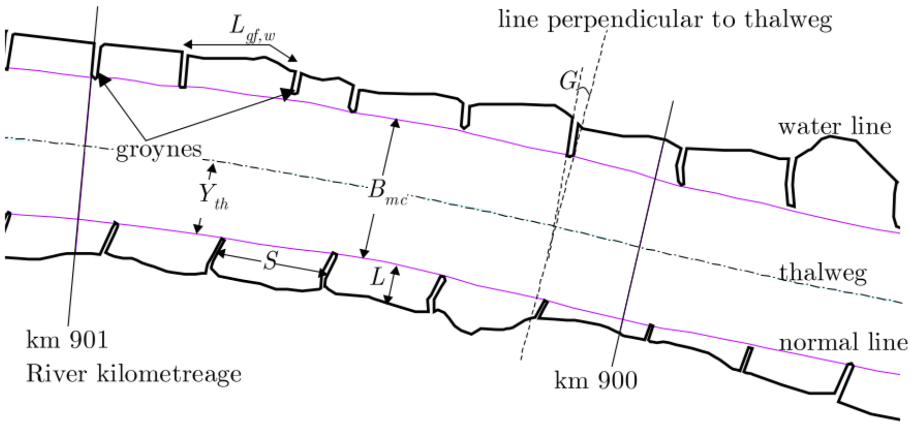


Figure 4.3: Definition of the characteristics of groynes (Yossef, 2005)

Based on the above described selection criteria a research location is selected. In figure 4.4 a photo of the research location is shown, it is located at Rhine km 910 at the northern side of the Waal river.

Figure 4.4: Research location

The location meets all the selection criteria. Water level and discharge data are available which can be used as model input and bottom level measurements are available to use for the bathymetry of the model. Furthermore the groyne(field) characteristics are regular and average Waal groynes:

- Spacing between groynes (200 m)
- Groyne length x width x height (106 m x 14 m x 4.5 m)
- Length along the waterline (204 m)
- Distance normal to main channel (115 m)
- Groyne orientation (-15 degrees)
- Bed slope (0.043)

Further, the research location is next to a proposed suitable groyne field of Rijkswaterstaat. This location is not exactly the proposed location, because a series of groyne is required.

To reduce the complexity of the model only one side of the river is taken into account. By doing so the domain is zoomed in to a spatial scale of a groyne field. In this way a sufficient small grid can be applied and the computing time will be limited.

This limitation of the model should be taken into account when assessing the model results and drawing conclusions in the end.

Grid and bathymetry

For the model a rectangular grid is used, because the research location fits within a rectangular shape. The grid is a staggered grid, this means output parameters are defined in the cell centres or at the cell interfaces. When an output variable is defined at the cell interfaces the output in the cell centre is obtained by interpolation of the output at the cell interfaces (4 surrounding grid points).

For a rectangular grid in XBeach a coordinate system is used where the computational x-axis is oriented towards the coast, perpendicular to the coastline, and the y-axis is alongshore. For this case the Dutch coordinate system is taken: RD New (EPSG:28992), because the bottom level multi-beam measurements done by Rijkswaterstaat, are related to that coordinate system. The coordinates of the origin of the grid are (163290, 433027). The domain is rotated with an angle of about 260 degrees counter-clockwise to fulfil the condition that the computational x-axis is perpendicular to the shoreline and the computational y-axis is parallel with the shoreline.

The grid size is taken such that in the first instance the hydrodynamic processes are visible in sufficient detail balanced with the amount of computing time required for a model run. A grid of 10 m x 10 m is chosen to start with, during calibration the impact of modifying the grid size is studied. It is expected that the grid contains enough resolution to model large-scale eddies, the unidirectional flow and the primary ship waves, which have a spatial scale of tens of meters. For the secondary waves the grid should possibly be refined.

The properties of the start grid (before calibration and validation) are:

- Size: 10 m x 10 m
- Total width: 270 m
- Total length: 1200 m
- Number of grid point on x-axis: 28
- Number of grid point on y-axis: 121

Next to a grid also a bathymetry needs to be loaded into the model by importing a depth profile. The bathymetry is created with the bottom level data, in appendix J.1 it is explained how this is done. Because the measured bathymetry is used instead of a schematised bathymetry it is expected that the model does not need to develop to an equilibrium bottom profile state first, which safes time. On the other hand it is not known if the (more or less) equilibrium bottom profile is measured. This uncertainty should be kept in mind when assessing the model results.

In figure 4.5 the bathymetry and the grid are shown with on the right an overview of the rotated research location. The groyne fields are numbered, so it is easy to refer to a specific groyne field in the following.

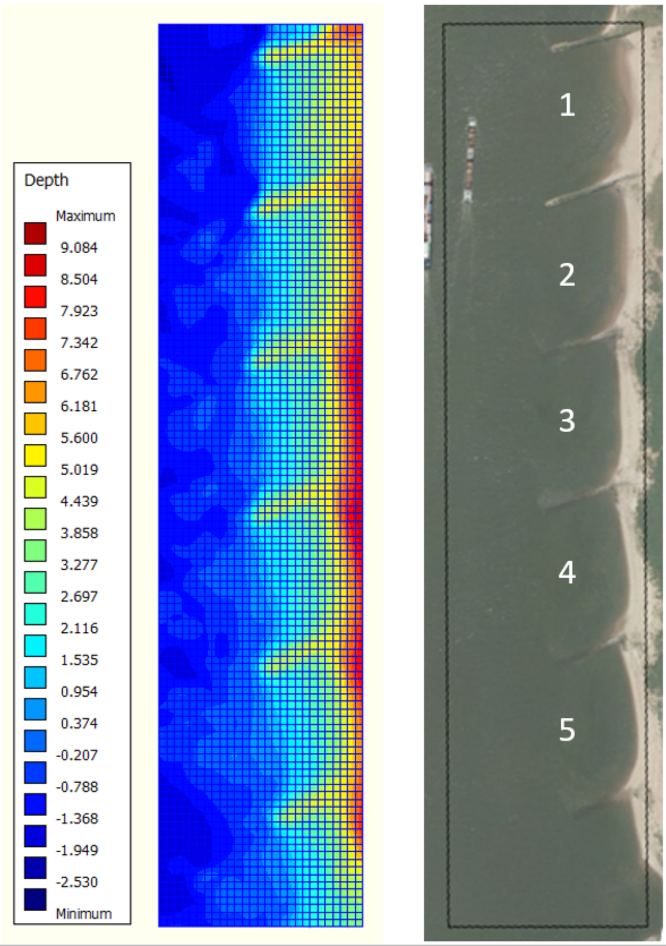


Figure 4.5: Left: grid + bathymetry; right: rotated overview of research location + numbering groyne fields

Boundary conditions

XBeach needs flow boundary conditions on all boundaries of the model domain. There are four boundaries along the model domain: the lateral boundaries, the boundary along the river bank and the boundary along the main channel.

At the main channel boundary of the domain the wave and currents generated in the domain need to pass through the boundary with minimal reflection. A weakly reflective-type boundary condition should be imposed at the boundary along the main channel. For a non-hydrostatic model a specific boundary conditions is set-up: the non-hydrostatic boundary condition.

Lateral boundaries are the boundaries perpendicular to the river bank. At these boundaries information should be prescribed about the area beyond the numerical model domain in such a way that the boundary condition does not influence the results in an adverse way. One way to do this is to prescribe a so-called “no-gradient”, Neumann boundaries, which state that there is locally no change in surface elevation and velocity.

At the boundary along the river bank a no flux wall boundary is imposed, assuming that river bank is non-absorbing and does not allow water to pass through.

Furthermore in XBeach also wave boundary conditions can be applied at the offshore side of the model domain to implement waves. Primary and secondary ship waves are simulated by schematising a ship by a pressure field moving with a certain speed through the domain. Ship waves are not forced at the offshore boundary by a wave boundary condition, therefore the wave boundary condition option is switched off.

Hydrodynamic mode

For simulating ship waves and when diffraction is an important process the non-hydrostatic mode should be applied to the model.

In the non-hydrostatic, the wave-resolving, mode the propagation and decay of individual waves can be simulated: the depth-averaged flow due to waves and currents are computed using non-linear shallow water equations, including a non-hydrostatic pressure. In the non-hydrostatic mode the wave asymmetry and the skewness are resolved.

Physical processes

XBeach can simulate a variety of physical processes which can be switched on or off. More generic processes, like waves and flow, are supported but also more specific processes like ship waves and point discharges.

For this research the hydrodynamics and the sediment transport induced by navigation and river discharge are simulated.

Also some physical processes are switched off, this will be shortly explained in the following.

Bed update is switched off because the grid size needs to be smaller than 1 x 1 m to get accurate results, which is expected to be not feasible. Furthermore the timescale of the erosion of the nourishment is significantly larger than for the passage of a ship which would results in (too) large computing time and computing power available for this research.

The effect of wind it not taken into account, because a river has a relatively small fetch.

Furthermore ground water flow is switched off. It is assumed that the ground water level is equal to the water level in the river and the soil close to the river mainly consists of sand. Therefore the ground water flow from the dry land to the river is assumed to be small and the effect of this flow on the flow pattern in a groyne field is assumed to be negligible.

Lastly the effect of vegetation (trees and bushes) is not considered, because no vegetation in the groyne field is present. Furthermore the river banks along the research location are only covered by grass and other small plant types.

Sediment transport

XBeach determines the sediment transport by looking at the mismatch between the actual sediment concentration and the equilibrium concentration.

XBeach calculates the sediment concentrations by using a depth-averaged advection-diffusion equation with a source-sink term based on equilibrium sediment concentrations. In formula 4.6 C represents the depth-averaged sediment concentration and Dh is the sediment diffusion coefficient. Ts is the adaptation time, which indicates how fast the sediment responds.

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial hCv^E}{\partial y} + \frac{\partial}{\partial x}\left[D_h h \frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_h h \frac{\partial C}{\partial y}\right] = \frac{hC_{eq} - hC}{T_s}$$

Figure 4.6: Depth-averaged advection-diffusion scheme with a source-sink term

When the depth-averaged sediment concentration (C) is higher than the equilibrium concentration (Ceq) there is deposition of sediment (sink) and vice versa sediment is entrained in the water column (source).

This is represented by the term on the right side of the equation.

XBeach calculates the equilibrium concentration for the bed and suspended load separately. The equilibrium sediment concentration Ceq (for both the bed load and the suspended load) is related to the velocity magnitude (vmg), the orbital velocity (urms) and the fall velocity (ws). The total equilibrium sediment concentration is calculated with the equation in formula 4.7.

$$C_{eq} = \max\left(\min\left(C_{eq,b}, \frac{1}{2}C_{\max}\right) + \min\left(C_{eq,s}, \frac{1}{2}C_{\max}\right), 0\right)$$

Figure 4.7: Total equilibrium sediment concentration

In XBeach two sediment transport formulations are available: Soulsby-Van Rijn and Van Thiel-Van Rijn. Since XBeach is focused on non-cohesive material, both sediment transport formula's are suitable for predicting (fine) sand transport. The two formulations calculate the equilibrium sediment concentration separately for the bed load and the suspended load transport by taking the effect of waves and currents into account. The general idea of these formulations is that if the sum of the mean flow velocity and the near-bed orbital velocity is larger than a critical velocity value, sediment is transported.

It should be kept in mind that these sediment transport formulas are focused on coastal areas, it is uncertain how these sediment transport formulas predict sediment transport in river areas.

In the XBeach manual the calculation of both sediment transport formulas is given. The difference between the two formulas is that Van Thiel-Van Rijn determines the critical velocity to mobilise sediment by taking the effect of currents and waves separately into account and Soulsby-Van Rijn uses a drag coefficient for this. Since the ship waves are generated by a moving pressure field instead of a wave boundary condition along the offshore boundary of the domain in the model the Soulsby-Van Rijn formula is used.

Sediment characteristics

The sediment transport depends among others on the sediment characteristics. In appendix J.2 the sediment characteristics of sediment in the Waal are elaborated.

From this literature study it appeared that the bed of the Waal consists of roughly of three sediment types: gravel, coarse sand and moderately coarse sand. From figure J.2 the D15, D50 (median grain size) and D85 are read. The applied sediment input parameters are given in 4.5. For the sediment density an average value is applied.

Table 4.5: Sediment characteristics for the Waal at the research location

D15 (m)	D50 (m)	D85 (m)	ρ_s (kg/m^3)
0.0005	0.0020	0.0070	2650

Time

The modelling time for the calibration and validation of the navigation processes in the model is set to 10 minutes, 600 seconds. It takes about 4 - 5 minutes for a ship to travel through the domain (sailing speed of 16 km/h over a distance of 1.2 km, see paragraph 4.3), the last 5 minutes are modelled to see if the water level will damp to the still water level.

The modelling time for the calibration of the river discharge is 24 hours, 86400 seconds, to be able to see if the model stays stable for different grid sizes. For the validation of the river discharge a shorter modelling time of 6 hours, 21600 seconds, is enough.

Output

Three types of output can be generated:

- Instantaneous spatial output: output that describes the instantaneous state of variables across the entire model domain at various points in time.
- Time-averaged spatial output: output that describes the time-averaged state of variables across the entire model domain at various points in time.
- Fixed point output: output that describes a time-series of one or more variables at one point in the model domain.

For each type of output a different time step can be defined.

The following quantities (and units) are considered for this research:

- Water level (m)
- Water depth (m)
- Flow velocity (m/s)
- Bed shear stress (N/m^2)
- Sediment concentration (m^3/m^3)
- Sediment transport (m^2/s)

For the output flow velocity a choice can be made between the Lagrangian (Generalised Lagrangian Mean (GLM)) velocity and the Eulerian velocity. Lagrangian velocity is defined as the distance a water particle travels in one wave period, divided by that period. The Eulerian velocity is defined as the short-wave averaged velocity in a fixed point. When adding up stokes drift to the Eulerian velocity the Lagrangian velocity is obtained. The Lagrangian velocity is taken as output.

4.3 Model Forcing

In this section the model forcing by navigation and river discharge is elaborated. A literature study is done to the characteristics of all three model input.

Navigation

The moving pressure field, the ship, is simulated by defining the ship's geometries and trajectory. A literature research is done to establish the characteristics of the navigation sailing on the Waal river: what types of ship are passing the groyne fields at what speed? What is the distance between the ship and the river bank. In the following a summery is given of this research. This literature study can be found in appendix J.3.

With the information of the literature study regarding the navigation characteristics on the Waal and the ship registration data (a sample of ship types that pass the Waal and their distance to the river bank) the ship wave input files are set up. In table 4.6 the ship is defined for which input files are made. To this ship will be referred to when setting up the scenario's later on.

A push convoy is chosen to model, because for this type of ship the effects in the groyne field are the most pronounced. These ship are the biggest and the least streamlined, therefore the waves and the currents induced by the ship are larger than for smaller, more streamlined motor ships. Furthermore, during field measurements in groyne fields along the Waal near Druten in 1984 (Havinga, Slootweg, & Zeekant, 1984), it was noticed that only push convoys cause a sufficient increase in flow velocity to bring the sediment in the groyne fields into motion.

The depth profile of the push-convoys is a rectangular pressure field with a depth corresponding with the ships draught.

Table 4.6: Ship properties

Type	Push-convoy
Length (m)	195
Width (m)	32
Draught (m)	3.50
Number of grid points x-axis	16
Number of grid points y-axis	39
Grid size x-axis (m)	2
Grid size y-axis (m)	5
Centre of gravity (x,y,z) (m)	(16,97.5,0)
Speed (km/h)	16
Distance to river bank (m)	150

The trajectory of the ship is defined by defining the position (x- and y-coordinates) in time based on the sailing speed of 16 km/h and the distance to the river bank is 150 m. The sailing speed and the distance to the river bank are based on the ship registration data looking at the push-convoys sailing downstream.

The ship is assumed to be loaded and travel from groyne field 5 to groyne field 1, so they travel downstream. In the trajectory also the z-coordinate is defined, which allows to let the ship "fly" into the domain and let the ship slowly "land" on the water to minimise boundary effect in the domain, what may improve the stability of the model.

River discharge

The river discharge is normally simulated in a hydrodynamic model by defining a discharge boundary condition at the upstream side of the domain and a water level boundary condition at the downstream side of the domain. After asking around and reading documentation about XBeach it was found that this is not possible in XBeach. Therefore the river discharge is simulated by defining point discharges at the lateral boundaries and imposing a constant water level relative to NAP in the complete model domain.

To simulate the continuous river discharge at two sections along the model boundary a discharge input is defined. At the downstream boundary water should be extracted from the model domain, so there a negative discharge is implemented. At the upstream boundary water should be added to the model domain, so there a positive discharge is implemented. By implementing a negative and a positive discharge of the same magnitude a flow through the model domain is created. Initially a wave travels through the model domain from the upstream boundary to the downstream boundary. There after the model needs time to damp out the initial conditions (spin-up time) and to develop to a stable stationary model containing a constant river discharge and a constant water level at a certain point in the model domain. The discharge and the direction of the discharge can be seen in figure 4.8.

It is known that this way of creating a discharge through the model domain often creates unstable models. An other option is to create this discharge by defining a water level difference along the domain, but this results in the same model with the same stability problems. Therefore in the calibration and validation the stability issues should be considered and should be limited as much as possible.

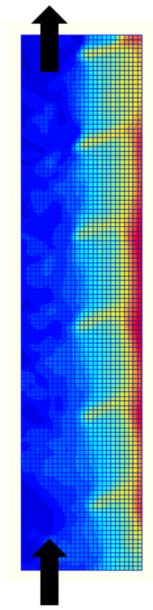


Figure 4.8: Location discharge input and output, the river flow streams from bottom to top

Discharge and water level in the Waal

The averaged discharge of the Rhine is 2300 m^3/s and 2/3 of this discharge flows into the Waal and 1/3 into the Pannerdensch Kanaal. So the average discharge in the Waal is around 1500 m^3/s, assuming the discharged water only flows into the Waal or the Pannerdensch kanaal (Ten Brinke, 2004).

High water flow conditions occurs when the discharge in the Waal is above 5400 m^3/s (Rijkswaterstaat Waterinfo, n.d.).

The lowered groynes along the Waal, between Nijmegen and Tiel, will become submerged during a discharge of about 2000 m^3/s at Lobith. This is the case for less than half of the year (165 days a year). The groynes located upstream of Nijmegen are not lowered, these groynes got submerged during a discharge of about 3500 m^3/s at Lobith. This happens for 1.5 months per year.

With the water level duration line of 2018 (Ned: waterstandsduurlijn en betrekkinglijnen) of the Rhine, published by Rijkswaterstaat every two years, the water levels and corresponding discharges can be looked up for every location in the Rhine. Furthermore an more detailed discharge distribution is published by Rijkswaterstaat. These two documents are used to define the water level and discharge at the research location.

River discharge input files

The river discharge induces, depending on the flow condition, large-scale eddies and/or unidirectional flow in the groyne fields. Therefore three flow conditions (water level with corresponding discharge) will be defined to be able to determine if XBeach is capable of simulating different flow conditions in rivers and groyne fields.

For setting up the input file for the three flow conditions a couple of factors should be in balance with each other to get a relatively stable model: the discharge flowing in and out at the lateral boundaries, the water level that is defined of the whole domain and the width of the discharge section. Furthermore the flow conditions should be realistic for actual flow conditions in the Waal, for this the water level duration line and the discharge distribution of the Waal of Rijkswaterstaat are used. An iterative process is used, where little changes were done to the input values of the factor, to obtain in the end the input files for a stable river discharge (for a grid size of 10 m x 10 m).

The final three flow conditions are given in table 4.7. For this specific low flow condition and the middle flow conditions in the Waal the flow conditions in the Waal are 66 and 248 days per year lower respectively. The groynes get submerged for a river discharge of 2000 m^3/s at Lobith, the flow conditions in the Waal are about 200 day lower per year.

Table 4.7: Flow conditions

Flow condition	**Water level (NAP +m)**	**Discharge Lobith (m^3/s)**	**Discharge Waal (m^3/s)**	**Input discharge (m^3/s)**
Low discharge (emerged groynes)	3.5	1350	900	430
Middle discharge (submerged groynes, low submergence level)	5.0	2370	1580	930
High discharge (submerged groynes, high submergence level)	6.5	3790	2527	1900

4.4 Elementary model test

To confirm that the model simulates the hydrodynamic processes and the sediment transport in a groyne field, a elementary model test is done.

For the river discharge a balance between the water level, the discharge and inflow cross-sectional area is searched for. For the navigation the impact of the incoming ship on the water movement (boundary effects) is minimised by adjustments to the trajectory.

Furthermore the model results can be improved by adjusting model parameters. In earlier research, to the simulation of ship induced water motion by a moving pressure field method in XBeach, two model parameters were suggested that can be adjusted to stabilise the model for a longer period of time: the grid size and the horizontal eddy viscosity (Zhou et al., 2013).

Horizontal eddy viscosity is a term in the momentum equations to cover the turbulence closure problem: there are more unknowns than equations. This problem implies that an infinite number of equations is required, which would be impossible to solve. Furthermore the horizontal eddy viscosity is useful numerically the increase model stability.

In appendix K the process of the elementary model test with the interim model results is described. For this test, and later for the validation, the forcing situations from table 4.8 are used.

Table 4.8: Forcing situations

	1	2	3	4	5	6
Ship	Push-convoy	Push-convoy	Push-convoy	-	-	-
River discharge	-	-	-	Low	Middle	High
Water level	Low	Middle	High	Low	Middle	High

The final model parameters are as follows:

- Simulating ship passage, no river discharge: grid size of 5 m x 5 m and a horizontal eddy viscosity of 0.25 m^2/s
- Simulating no ship passage, constant river discharge: grid size of 10 m x 10 m and a horizontal eddy viscosity of 0.25 m^2/s

When simulating a ship passage together with a constant river discharge the model parameters to keep the river discharge stable are governing, so a grid size of 10 m x 10 m and a horizontal eddy viscosity of 0.25 m^2/s is taken in this case.

4.5 Model validation

In this section the model will be validated for multiple forcing situations already given in table 4.8. The ship and the flow conditions are specified earlier in table 4.6 and table 4.7 respectively. By simulating the first three forcing situations it can be determined whether XBeach simulates ship waves correctly. The next three forcing situations are used to test the capability of XBeach to simulate different flow conditions. The model results will be validated with the literature study and the observations done during the visual inspection. Since no field measurements are done in the researched groyne field only data from literature is available for the validation. It should be kept in mind that it is likely that the model results deviate from the data as presented in literature. In table 4.9 for each forcing situation the hydrodynamic processes that are expected to be visible in the output of XBeach are marked by a (X).

Table 4.9: Expected hydrodynamic processes

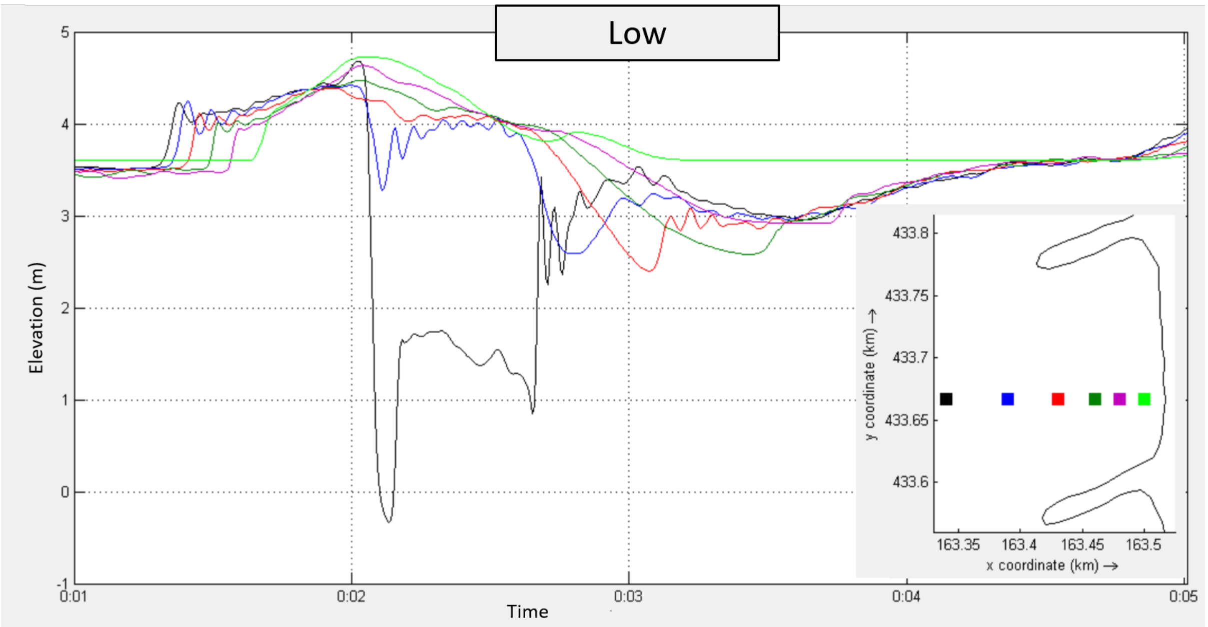
Forcing situation	**Primary waves**	**Secondary waves**	**Large-scale eddies**	**Unidirectional flow**
1	x	x		
2	x	x		
3	x	x		
4			x	
5			x	x
6				x

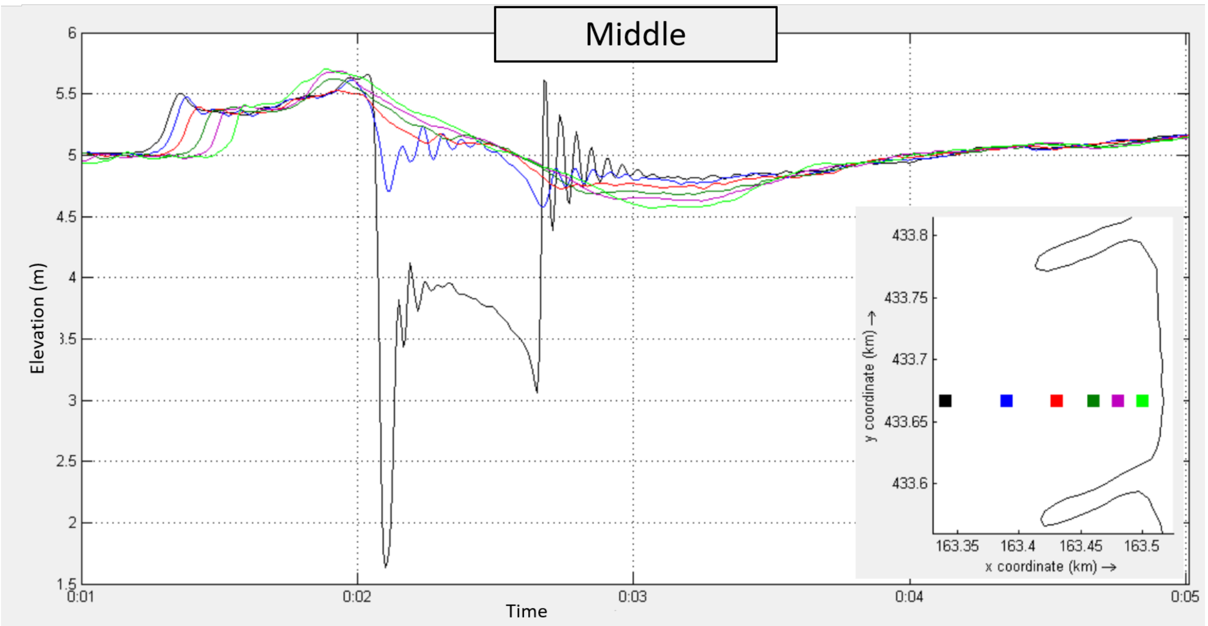
After validation the model results may be considered as accurate representation of the real system: hydrodynamics and sediment transport in a groyne field.

Navigation

From sub-research question 1 followed that the main hydrodynamic processes in a groyne field along the Waal due to navigation are forced by the primary and the secondary ship waves.

During the passage of a ship the hydrodynamics in a groyne field change every second, therefore time is an important aspect in the validation of the hydrodynamic processes in a groyne field induced by navigation.





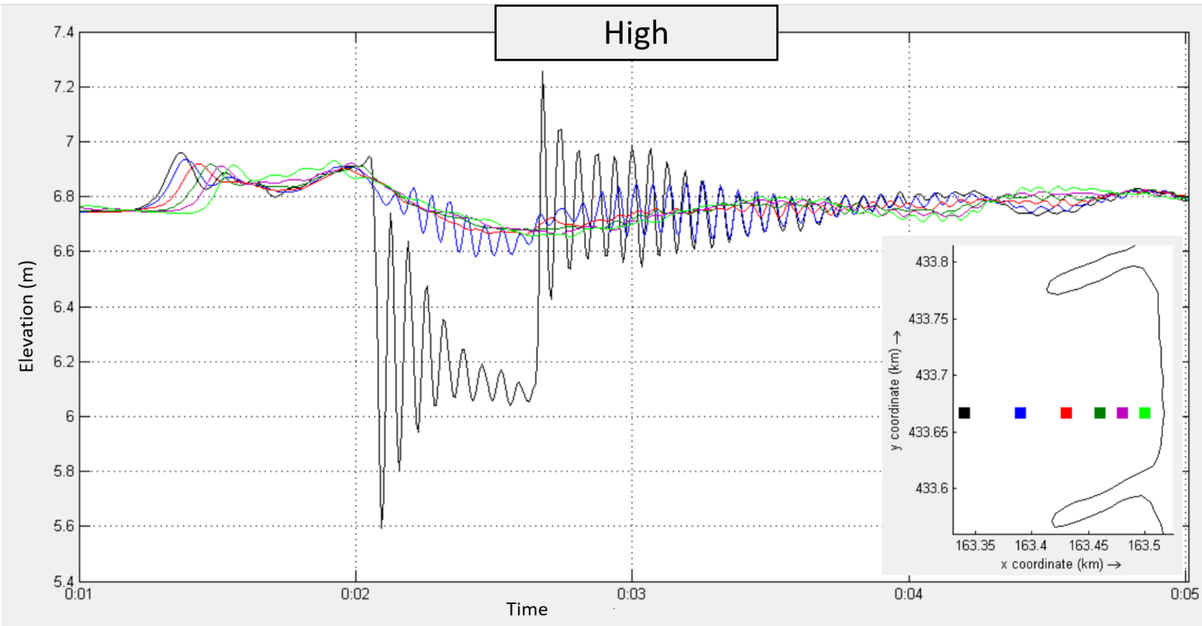


Figure 4.9: Water level (1D) during low (upper panel), middle (middle panel) and high water (lower panel). The colour of the line corresponds with the colour of the dot in the groyne field

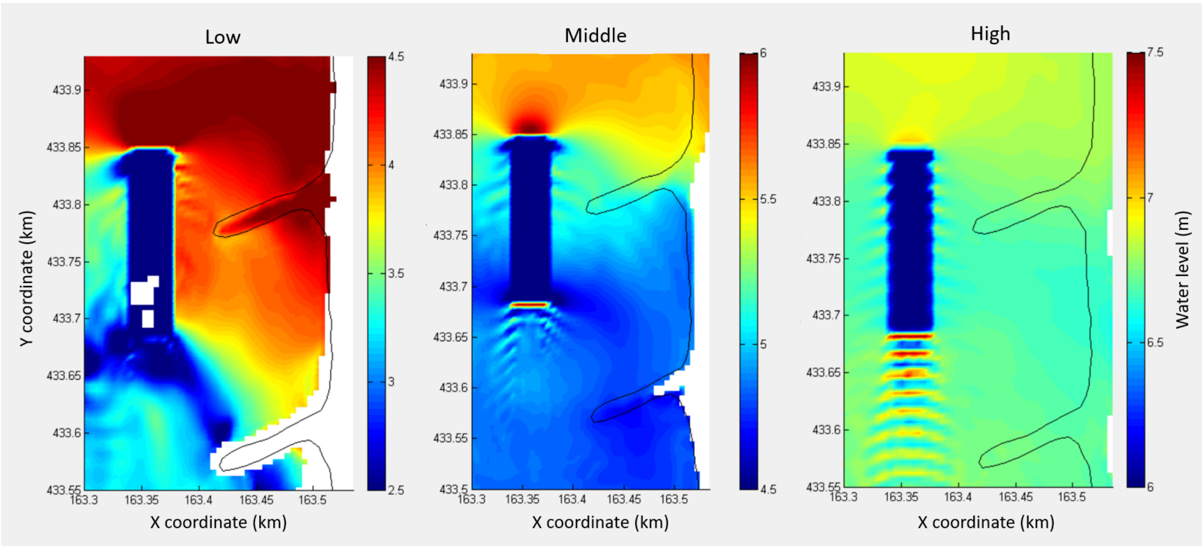


Figure 4.10: Water level 2D during low (left panel), middle (centre panel) and high water (right panel)

In figure 4.9 and 4.10 the water level in 1D and 2D for multiple locations along the x-axis of the groyne field are given for three water levels. The primary wave is clearly visible and for every water level secondary waves are generated along and behind the ship. The resulting wave height of the front wave next to the ship in the main channel (blue dot) is 0.8 m, 0.6 m and 0.2 m for low, middle and high water levels, respectively. The wave height of the stern wave next to the ship in the main channel (blue dot) is 0.6 m, 0.3 m and 0.1 m for low, middle and high water levels, respectively. These resulting wave heights are in the range for primary waves although the wave height is on the upper level (AnteaGroup, 2019). The wave periods of the front and stern waves are in the order of a couple seconds, except for the stern wave in case of low flow conditions. The water level depression has a duration of about 45 s. These characteristics are typical for primary waves (AnteaGroup, 2019). The secondary waves have a wave height of 0.4 m and a wave period of 4 s, which is typical for secondary waves (AnteaGroup, 2019).

For a high water level the secondary waves travel into the groyne field and reach the river bank. The wave height decreases during the propagation to the river bank, in the groyne field only small water level oscillations are visible. The largest decrease in wave height occur at the transition from the main channel bottom to the groyne field bottom. This region has a steep slope in the bottom profile of 1/5 or steeper (Yossef, 2005). This significant damping of the secondary waves may occur due to the decreasing water depth. In addition, the shoaling distance of waves on steeps slopes becomes relatively short and the waves may be partially reflected from the steep bottom (Tsai, Chen, & Huang, 2002). The water level oscillation that does occur in the groyne field does not damp further when propagating to the river bank, which is typical for secondary waves.

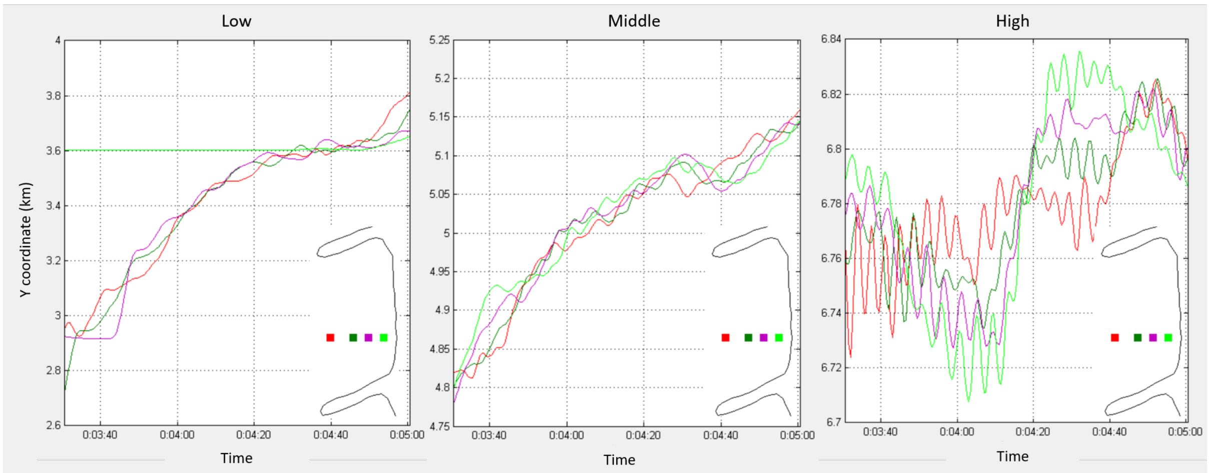


Figure 4.11: Zoom in on secondary waves

The quick damping of secondary waves at the transition from the main channel to the groyne field is more pronounced for low and middle water levels, since the water depth is even less. For a middle water level still water level oscillations are visible with the wave period of a secondary wave in figure 4.11. These oscillations do not further damp and propagate to the river bank. For a low water level the secondary waves are not visible anymore. The strength of the suction and supply currents increase for lower water levels, this may damp the secondary waves that propagate into the groyne field. During the visual inspection in the groyne field during low water (the groyne heads were 1 m above the water level, so the water level was about 3.5 m + NAP) the secondary waves were not visible. In the main channel the secondary waves were visible, but at the edge of the groyne field a lot of water movement (turbulence, eddy, currents etc) was going on after which the secondary waves disappear. So the model results seem to agree with the visual observation. The exact explanation for the disappearance of the secondary waves during low water level in the model is not completely clear. In the following, the validation of the resulting hydrodynamic behaviour in the groyne field is continued for low and middle water level, since for these two situations the navigation has an effect on the morphology in a groyne field according to the literature.

For the validation of the flow velocity (magnitude and direction) these four characteristic moments during the ship passage needs to be visible in the model results:

- The front wave travels into the groyne field and the water level increases; visible at time: 01:50
- The water level depression cause an emptying of the groyne field (suction); visible at time: 03:10
- The stern wave travels in the groyne field and the groyne field is filled up again by the supply flow, the in- and outflow meet, eddies form in case of low flow conditions); visible at time: 03:22
- The groyne field is almost filled up; visible at time: 03:48

In figure 4.12 the flow velocity magnitude and direction is given for the four moments for low and middle water level.

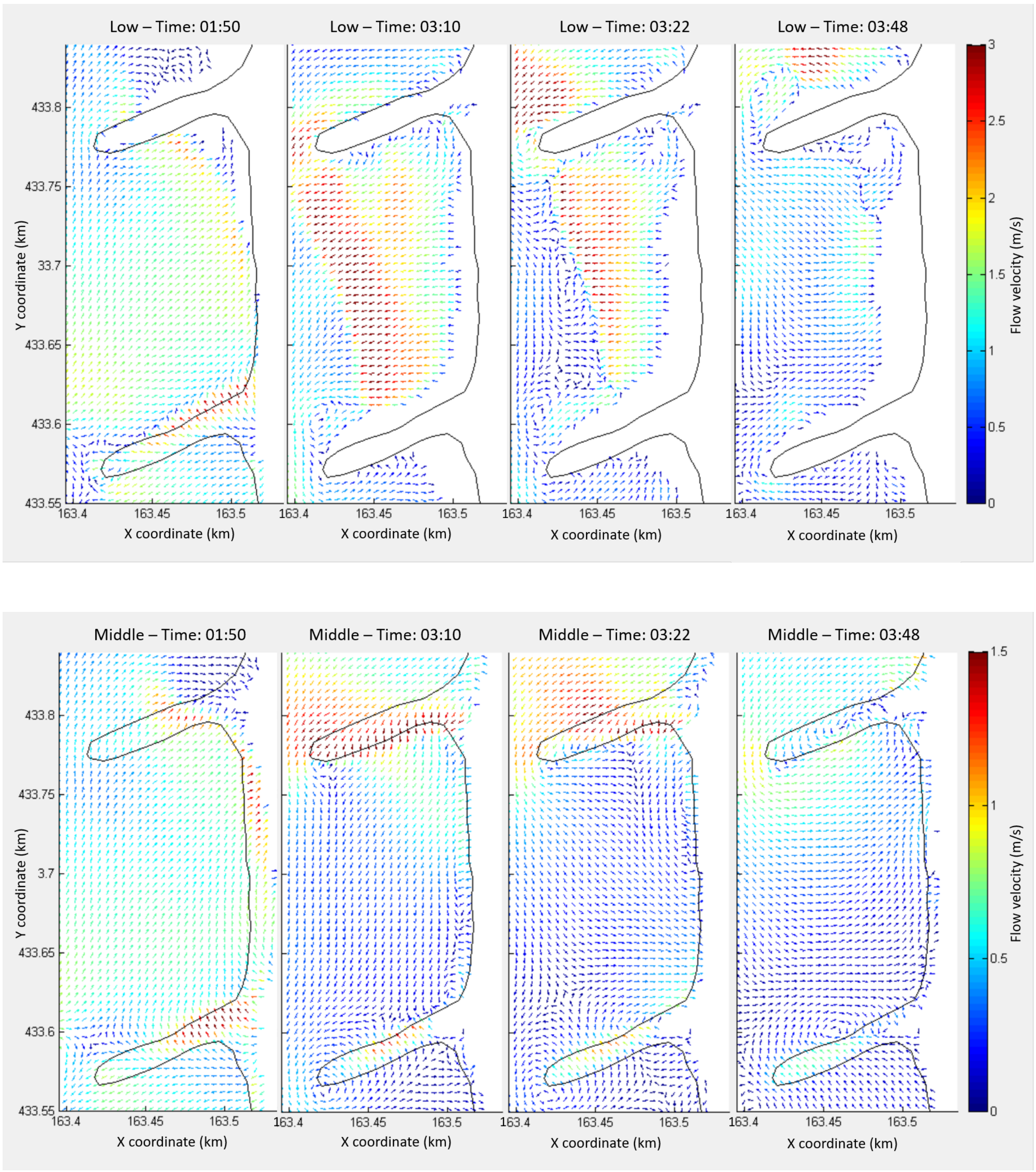


Figure 4.12: Flow velocity during the passage of a ship during low water level (emerged groyne) and medium water level (submerged groyne)

For both water levels the four characteristic moments are clearly visible in the model results. During low water level at the time 03:22 the results clearly show the forming of eddies in the groyne field. When comparing the results of the two different water level situations a big difference in the flow velocity magnitude can be observed: the currents are much stronger for low water. This is according the literature. The flow velocities induced by navigation can be up to 3 times higher, than the natural flow velocities in a groyne field induced by river flow (AnteaGroup, 2019). When comparing the flow velocities induced by navigation with the flow velocities induced by river discharge (figure 4.18) for both water level situations: the flow velocities induced by navigation are more or less 3 times stronger during low water and for middle water the flow velocities are about 2 times stronger.

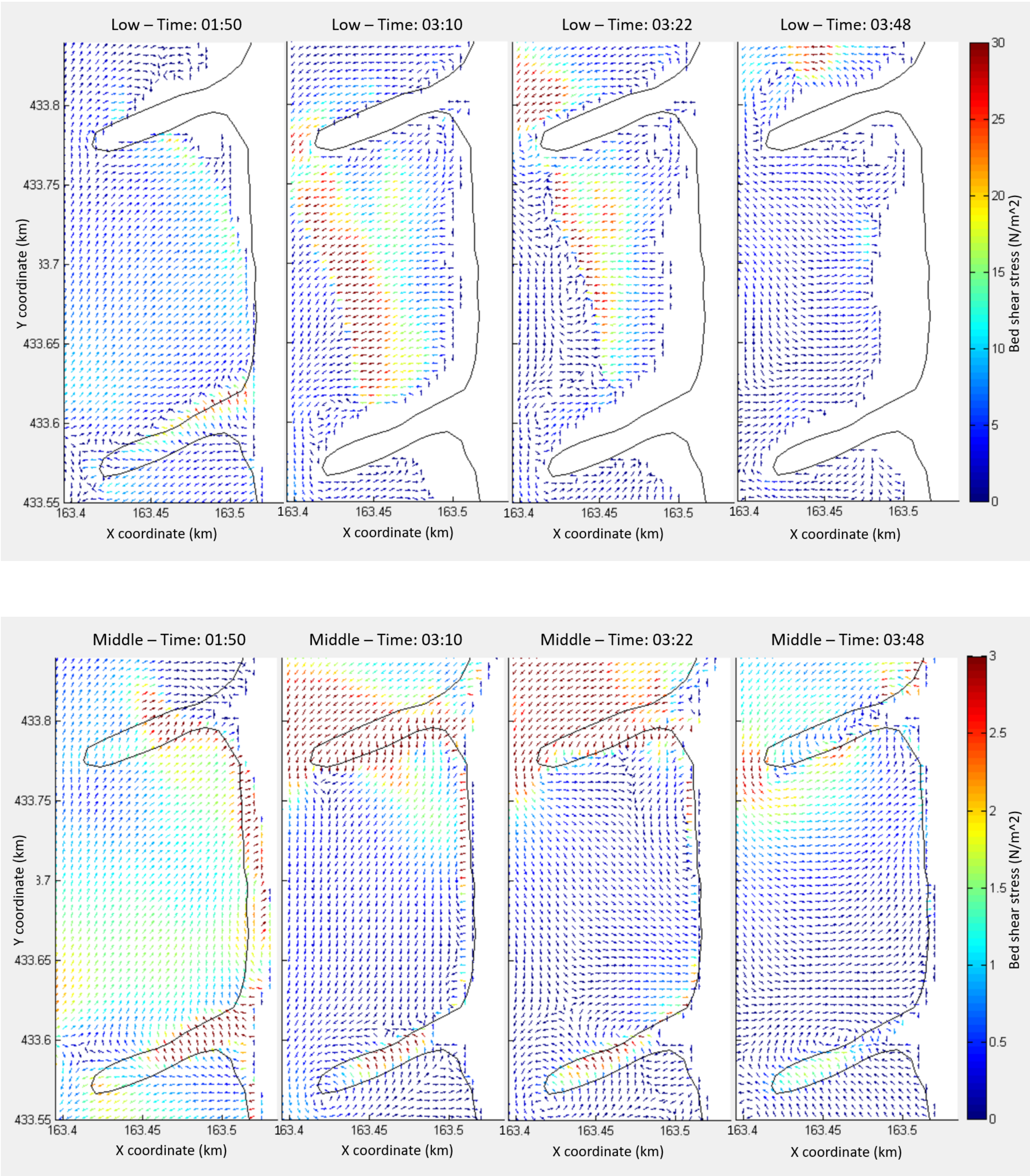


Figure 4.13: Bed shear stress during the passage of a ship

In figure 4.13 the bed shear stress magnitude and direction is given for the four moments for low and middle water level. It can be seen that the bed shear stress follows the flow velocity in magnitude and direction variation over the groyne field during the passage of the ship. This should be the case because the bed shear stress is directly calculated from the flow velocities by using the approach of Ruessink (dimensionless friction coefficient calculated with Chézy, C in the order of 55 $m^{1/2}/s$ (Roelvink et al., 2015)). The used formula's can be found in the public XBeach user manual.

To be able to check if the bed shear stress output of XBeach will cause mobilisation of the sediment, the Shields approach is used. With the Shields approach the critical bed shear stress, that is needed to mobilise the bottom material located in the groyne field, is calculated. For this calculation the median grain size is used, while the sediment consist of a range of grain sizes. Therefore the calculated critical bed shear stress holds for the median grain size, but can be less or higher for the other grain sizes in the sediment.

It is known that the median grain size (D50) in the groyne field is 2 mm. The acceleration of gravity is 9.81 m/s^2; the viscosity is $1.33 * 10^{-6}$; the density of the sediment is $2650kg/m^3$ and the density of the water is $1000kg/m^3$.

$$\Delta = \frac{(\rho_s - \rho_w)}{1000} = \frac{(2650 - 1000)}{1000} = 1.65$$

$$d_* = d * \left(\frac{\Delta * g}{v^2}\right)^{\left(\frac{1}{3}\right)} = 0.002 * \left(\frac{1.65 * 9.81}{(1.33 * 10^{-6})^2}\right)^{\left(\frac{1}{3}\right)} = 41.83$$

When looking at the Shields diagram in 4.14: for a dimensionless particle diameter of 41.83 the Shields parameter is 0.04.

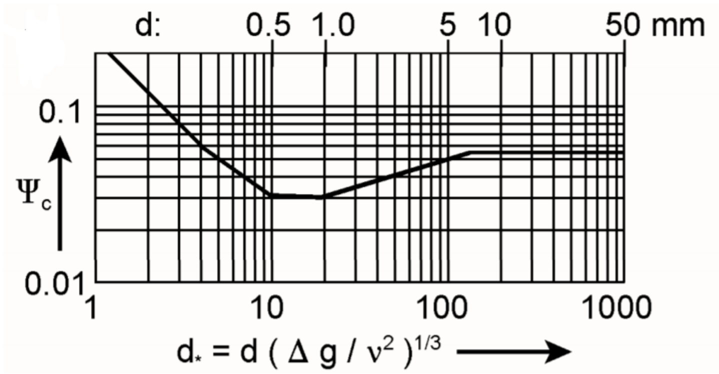


Figure 4.14: Shields relation (Schiereck & Verhagen, 2016)

$$\psi_c = 0.04$$

Now the critical shear stress can be calculated. This is the minimum shear stress needed to get a particle with a diameter of 2 mm in motion.

$$\tau_c = \psi_c * (\rho_s - \rho_w) * g * d = 0.04 * (2650 - 1000) * 9.81 * 0.002 = 1.29 \frac{N}{m^2}$$

So the bed particles are brought in motion when the bed shear stress is equal or higher than 1.30 N/m^2. When the bed shear stress output of the two water level are compared and taking into account the critical shear stress, a great difference in bed shear stress magnitude can be seen. For low water (emerged groynes) it can be expected that when the groyne field is emptied by suction a lot of sediment is brought in motion and transported in the direction of the main channel. While for middle water (submerged groynes) only at some moments the bed shear stress exceeded the critical bed shear stress of 1.30 N/m^2. This happens when the front wave travels into the groyne field. This corresponds to the literature in which is said that the effect of navigation on the morphology of the groyne field is large during emerged groynes and quickly decreases when the groynes water level increases and the groynes get submerged (Ten Brinke, 2004).

In the following only for low water the sediment concentration and sediment transport is elaborated. For high and middle water level very less to no sediment entrainment and transport is expected and this also follows from the model output.

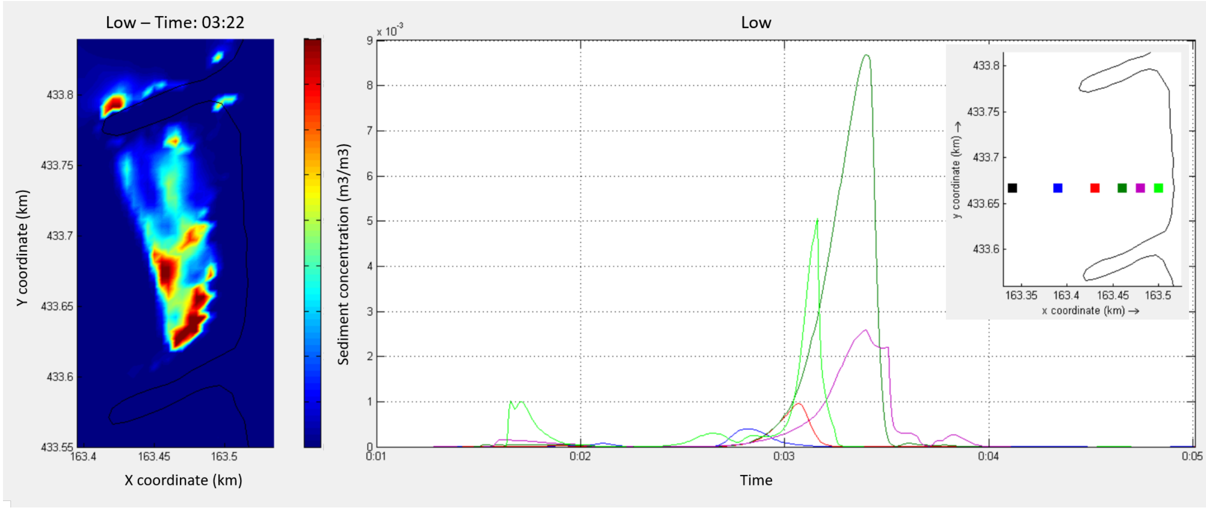


Figure 4.15: Left: Sediment concentration (2D); Right: Sediment concentration (1D)

In figure 4.15 the sediment concentration in time is given for multiple locations along the centre x-axis of the groyne field. It can be seen that the highest sediment concentrations occur in the right half of the groyne field, because in this part of the groyne field the water depth is much less than at the blue and red location due to the steep slope to the main channel. The highest sediment concentrations at each locations occur during the emptying of the groyne field by suction. This corresponds to the high flow velocities and bed shear stresses at the moment and location. The sediment concentrations at 03:22 are given in the whole groyne field in the left panel of the figure. The scale for the colour scale bar is the same as for the graph on the right.

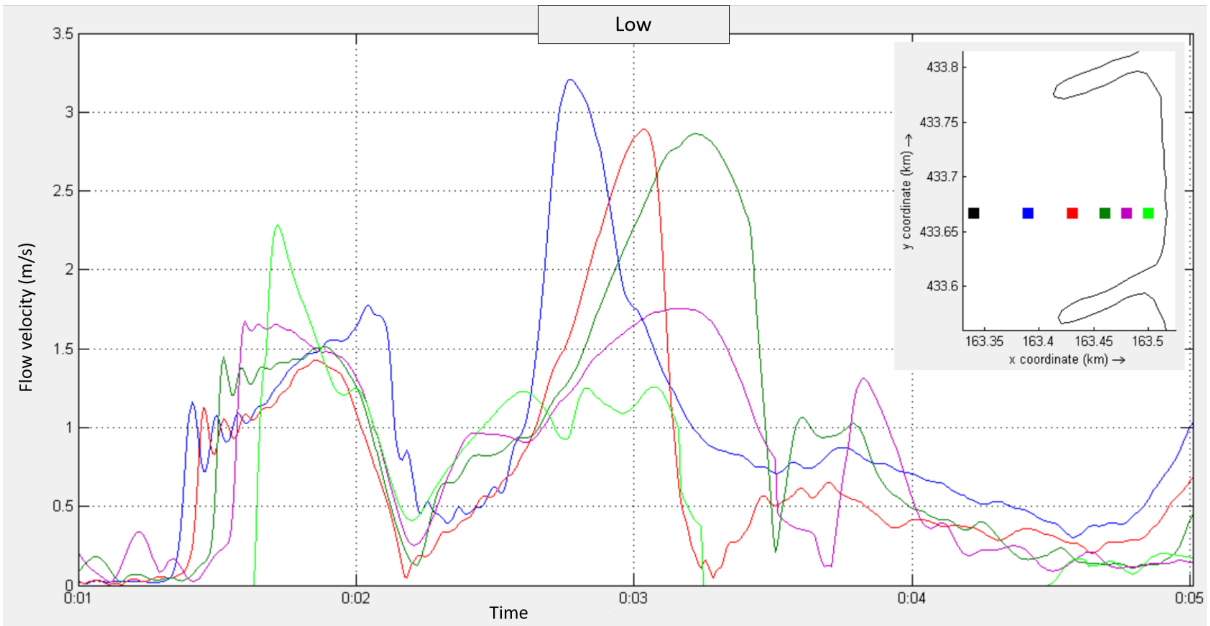


Figure 4.16: Flow velocity during the passage of a ship

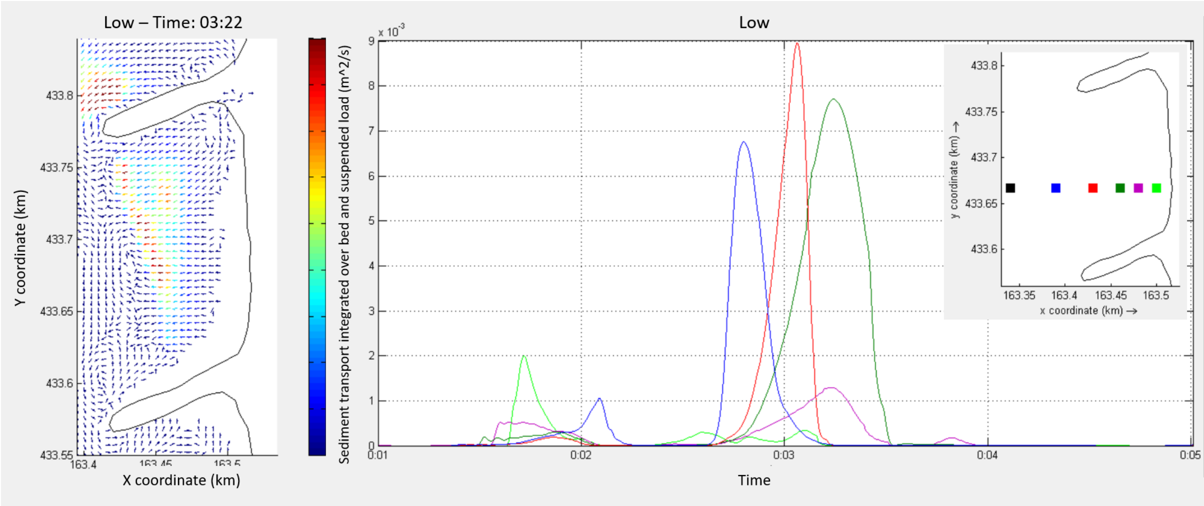


Figure 4.17: Left: Sediment transport (2D); Right: Sediment transport (1D)

A gradient in the sediment concentration causes sediment transport. Furthermore the high flow velocities in combination with the sediment concentration at that moment in the water results in sediment transport. The flow velocities in time for the same locations can be found in figure 4.16. The sediment transport rates for the same location can be found in figure 4.17 in the right panel. In the left panel the sediment transport magnitude and direction can be found at 03:22. The colour scale bar has the same scale as the graph. It can be seen that suction starts to erode sediment at the groyne field edge, this erosion effect of suction propagates towards the centre of the groyne field and thereafter slowly the strength of the suction currents decreases and the erosion effect decreases also.

It appears that XBeach simulates the primary wave system during emerged and submerged groynes. XBeach can also simulate secondary waves in case of submerged groynes, but in the case of emerged groynes the secondary waves are hardly visible in the model results. This corresponds with the visual inspection, but not with the literature study done in chapter 2. Therefore it remains unclear if XBeach simulates the (probably damped) secondary waves accurately. This uncertainty is taken into account in the remainder of this research. Statements about the effects of secondary waves during emerged groynes on the behaviour of the nourishment are based on the literature study.

River discharge

From sub-research question 1 it follows that the main hydrodynamic processes in a groyne field along the Waal are the large-scale eddies and the unidirectional flow or a combination of those two depending on the flow conditions.

When the model for this constant discharge scenario is fully developed the water level and the hydrodynamic processes in a groyne field during a certain discharge condition are constant in time although small instabilities occur.

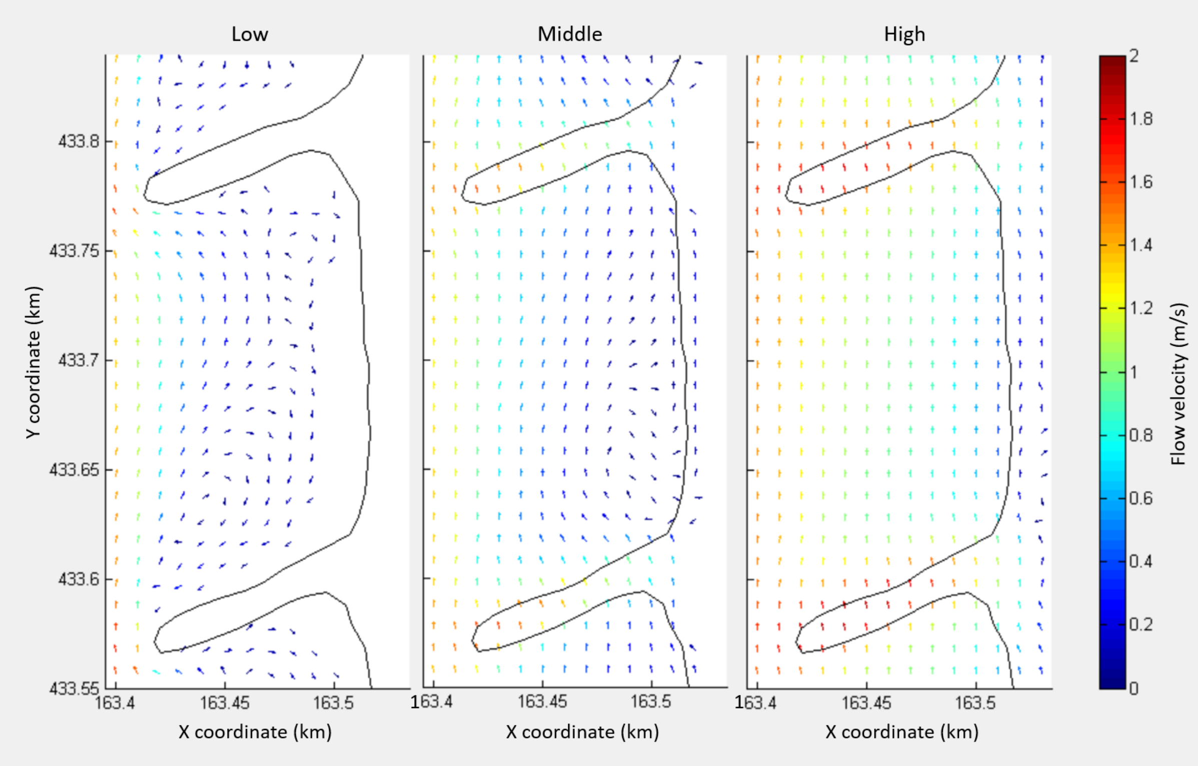


Figure 4.18: Flow velocity for low (left), middle (centre) and high (right) flow conditions

In figure 4.18 the magnitude and the direction flow velocity is given for three flow conditions. For low flow conditions the primary eddy is visible in the 2/3 upstream part over the full width of the groyne field. The secondary eddy is located upstream of the second groyne close to the river bank. The flow pattern in the groyne field in case of emerged groynes is therefore simulated accurately. The combination of unidirectional flow and large-scale eddies are simulated accurately for middle flow conditions. An large eddy is situated close to the river bank in the upstream part of the groyne field. In the other parts of the groyne field the unidirectional flow is dominant. For high flow conditions the unidirectional flow can be seen in the whole groyne field. These observations are according to what is expected based on the literature study done for sub-research question 1.

For low flow conditions the primary eddy should have a flow velocity of about 30% of the main channel flow velocity and the secondary flow velocity should be about 30% of the primary eddy flow velocity (Ten Brinke, 2003). The primary eddy flow velocity should be in the range of 0.3 to 0.4 m/s (Yossef, 2005) and the primary flow velocity according the model results is about 0.4 m/s, so this satisfies. According to the 30% indication rule, the main flow velocity in the main channel should be 1.2 m/s and the flow velocity in the secondary eddy 0.13 m/s. When looking at the model results of the flow velocity in figure 4.18 the flow velocity in the main channel is about 1.3 m/s, so this is accurate.

For high flow conditions the flow velocity in the main channel and in the groyne field increases. As indication to see if this increase is accurate a validated reference model is used: a WAQUA model for a groyne field along the north side of the Waal at 894.3 kmr during a discharge of 4000 m^3/s at Lobith. This model gives a flow velocity in the main channel of 1.4 m/s and in the groyne field average flow velocity of about 0.7 m/s. The XBeach model results approaches these flow velocities.

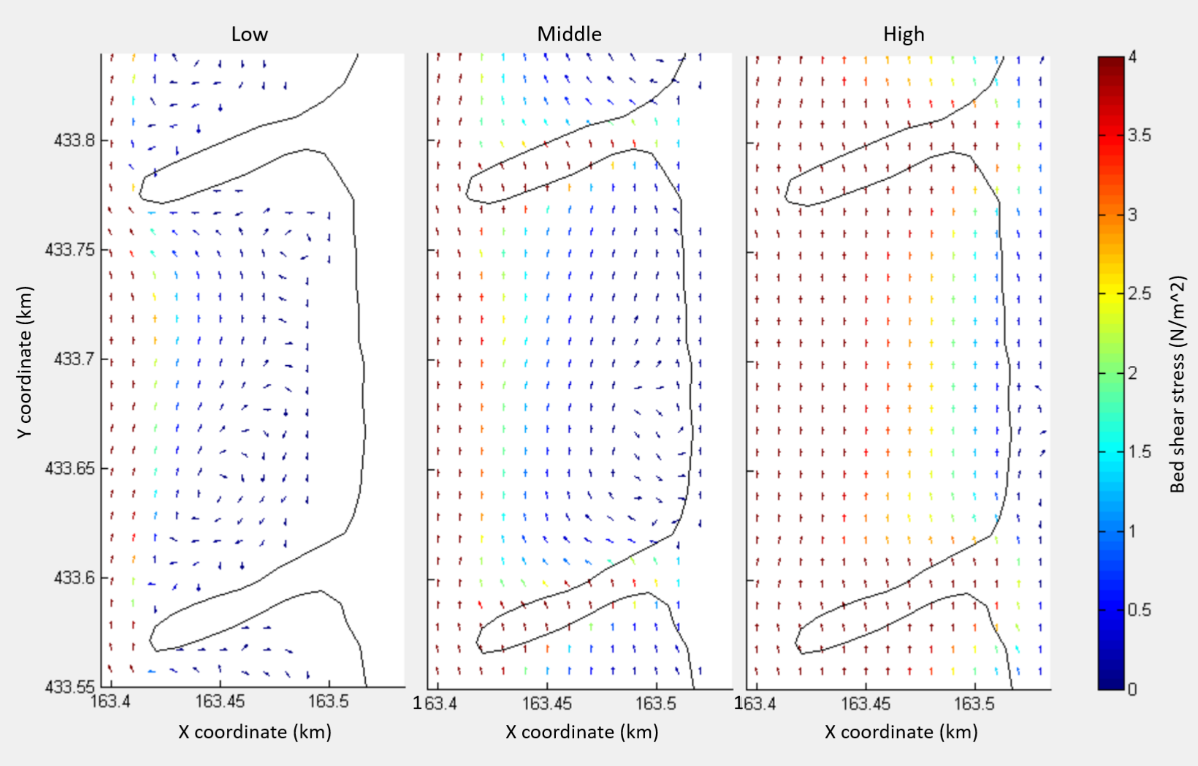


Figure 4.19: Bed shear stress for low (left), middle (centre) and high (right) flow conditions

The bed shear stress should follow the direction and the gradients in the flow velocity according to the literature. In figure 4.19 the bed shear stress for the three flow conditions are given.

For realistic results, the bed shear stresses induced by the river discharge should be, during low and middle flow conditions, too weak to mobilise sand (bed shear stress below 1.30 N/m^2). During a low and middle flow condition, the hydrodynamic processes in the groyne field are too weak to mobilise sediment.

When looking at figure 4.19 it can be seen that the bed shear stress model output for low and middle flow conditions comply to this. For high flow conditions the flow velocity is relative high and with that also the bed shear stress becomes higher. For high flow conditions the critical bed shear stress is exceeded and in this situation the high river discharge induces entrainment of the sediment.

From the bed shear stress results should follow that for low and middle flow conditions the sediment concentration in the groyne field is zero since no other forcing is present in the model that could induce sediment entrainment. For high flow conditions sediment is brought in suspension, so a non-zero sediment concentration is expected. No data was found in the literature about sediment concentrations in groyne fields during high flow conditions in the Waal.

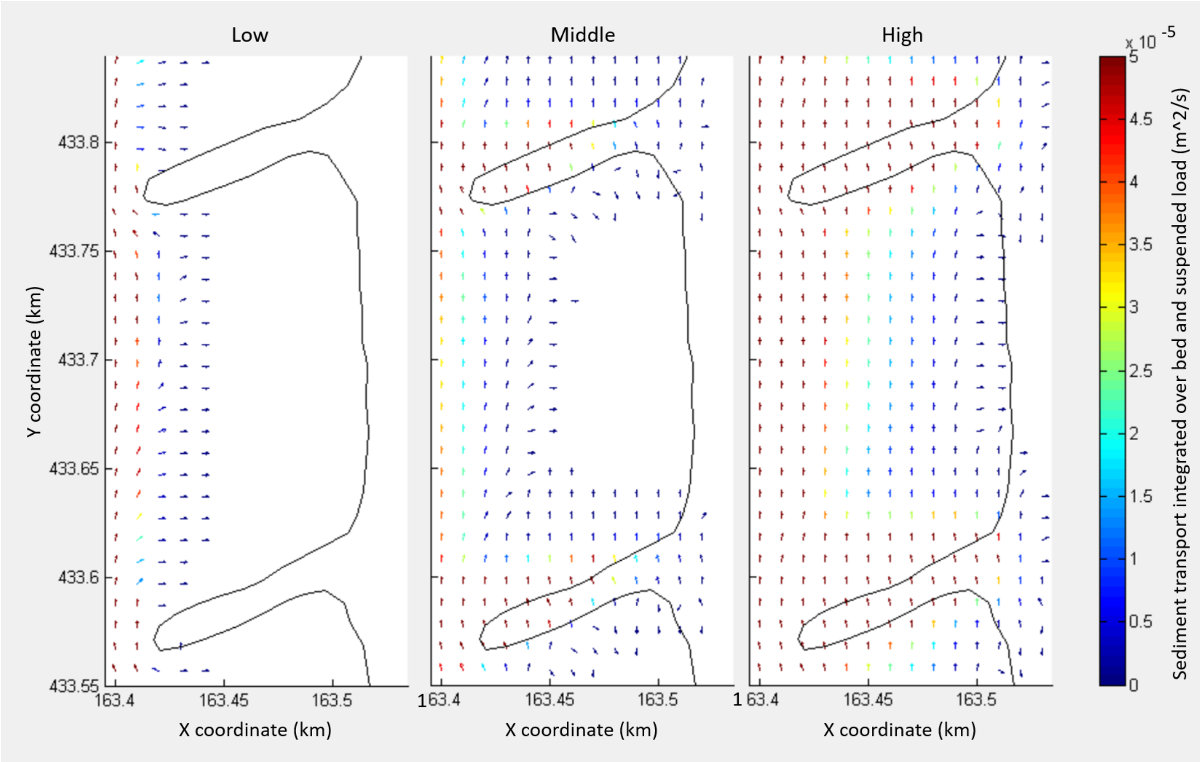


Figure 4.20: Sediment transport for low (left), middle (centre) and high (right) flow conditions

The gradients in the sediment concentration cause sediment transport. In figure 4.20 the sediment transport for the three flow conditions is given. The sediment transport is a bit distorted in the model on and along the groynes due to modelling the groyne as a high sediment concentration which is not true in reality. But still it can be seen that during low and middle flow conditions the river discharge causes sediment import into the groyne field. For high flow conditions it can be seen that the net sediment transport is zero, since the same sediment transport rate is present at the groyne. These model results are in accordance with the literature.

In the end it appears that XBeach accurately simulates the flow pattern in the groyne field induced by the river discharge for the three flow conditions. The flow patterns and the flow velocity magnitudes found in the literature are also accurately simulated.

5. Numerical model results for different nourishment locations

In this chapter the base model, described in chapter 4, will be modified by placing different types of nourishments in groyne field 3. The base model bathymetry is modified by hand to add the nourishments. Based on the literature study of chapter 2 and the analogies of chapter 3 three nourishment types will be proposed that may function as small feeder nourishment that supplies slowly sediment to the main channel. The model results (flow pattern, bed shear stress etc.) in case of the three nourishments will be compared to each other to be able to give an answer to sub-research question 3: How does the type of nourishment (shape and location) influence the way in a nourishment will act as a small feeder nourishment that slowly releases sediment to the main channel?

5.1 Nourishment parameters

Four important nourishment parameters are volume, material, shape and location. All four parameters will be elaborated in the following, but this research is focused on the location and shape of the nourishment. These two parameters will be researched with the XBeach model. The material and the volume are for all three nourishment the same. In this way the comparison between nourishments is more valuable since no differences in the model results can be contributed to nourishment volume differences.

Volume

From the preliminary research of Rijkswaterstaat it can be said that the dumping volume of groyne fields along the Waal varies within a range of 2600 m^3 to 18,000 m^3 with an average of 5000 m^3 (Tönis, 2019).

During the practical test to research if a nourishment can protect a groyne field bottom against erosion by Rijkswaterstaat, elaborated in section 3.5, an average volume of about 10,000 m^3 was dumped in the groyne fields (Duijn, 1996). This volume was dumped over the full length of the nourishment.

Based on these number a nourishment volume of 5000 m^3 is chosen for the three nourishment types.

Location

From the analogy with a coastal nourishment the groyne field nourishment seems to be the most effective and efficient at location 3 or 4 in figure 5.1. Location 3 in a groyne field is next to the river bank and location 4 is the part of the groyne field that is most of the time submerged, about the 2/3 of the groyne field width the closest to the main channel.

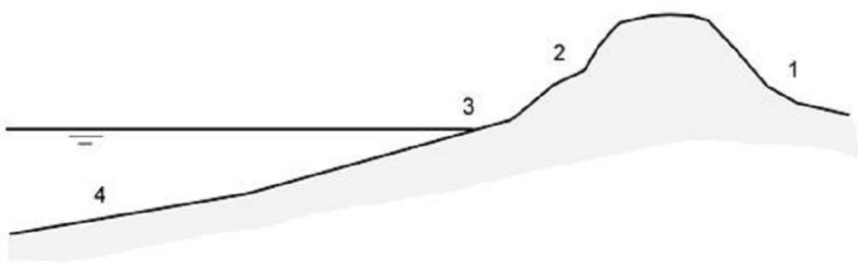


Figure 5.1: Possible nourishment locations (Bosboom & Stive, 2015)

Adding to this, Rijkswaterstaat has done a research to the protection of a river bank and groyne field bottom against erosion by placing a nourishment in the groyne field. For this research a practical test was done by placing a nourishment of 1.5 m thick, along the full length of a groyne field (about 150 m) at approximately the outer slope of the river bank (nourishment reaches over an area of 35 m from the steep edge of the river bank into the groyne field), this corresponds with location 3 in figure 3.7. This type of nourishment was applied in three groyne fields situated along the northern side of the Waal near Ewijk (Rhine km 893) (Duijn, 1996).

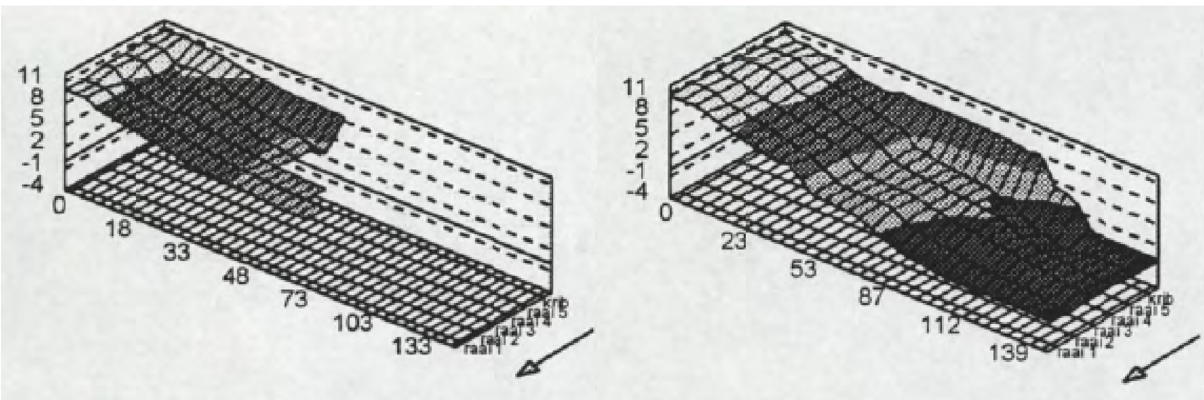


Figure 5.2: Left: bottom profile groyne field in September 1989; right: bottom profile groyne field in June 1893 (Duijn, 1996)

After a period of 4 years (including two long-term high water conditions) of monitoring the morphology in the groyne fields, it appeared that the nourishment can protect the groyne field bottoms for a long period since a small amount of sand was eroded out of the groyne field (close to the groyne heads). Furthermore 20 % of the initial supplied sand was moved further into the groyne field, but stayed in the groyne field (Duijn, 1996). In figure5.2 the displacement of the sand can be seen, the arrow gives the flow direction in the river.

From the above it seems that nourished material at location 3 will mainly not be transported to the main channel of the river. So location 4 is the proposed location area for the nourishment that should work as small feeder nourishment that will release slowly sediment to the main channel. When designing a nourishment that will be placed at location 4, it should be kept in mind that the nourishment stays clear from the steep groyne field edge along the main channel side. If not, the nourished material will roll directly into the main channel due to avalanching. Then dredging works probably needs to be done to keep the main channel navigable.

In the 3D visualisation of the bottom profile in figure 5.3 this steep edge can be seen. The nourishment should be placed within the area about 25 m from the groyne head and 25 m from the river bank.

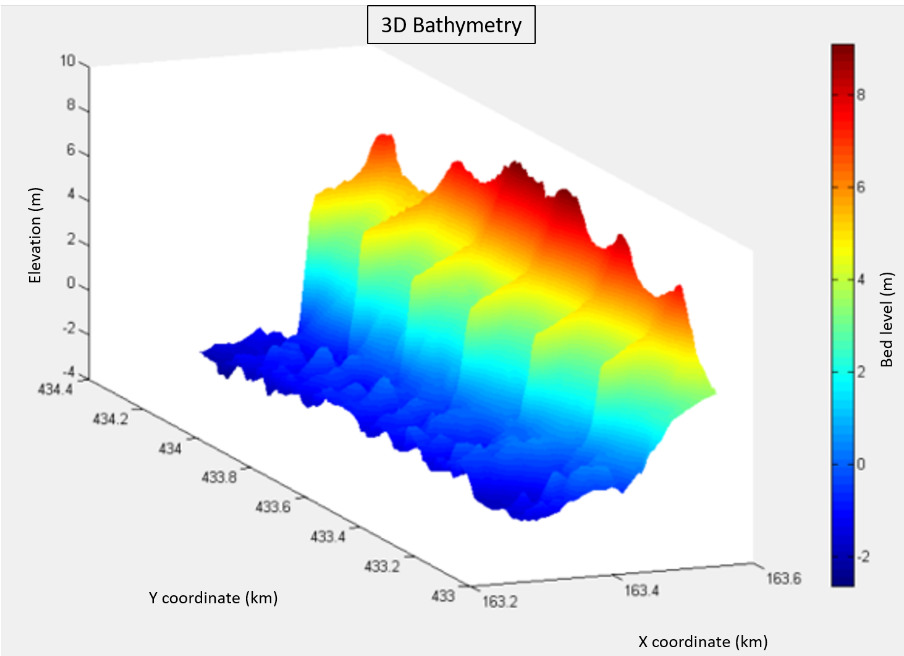


Figure 5.3: 3D bottom profile of the series groyne fields along the Waal

Material

The objective of the nourished material in the groyne field is that it will be slowly transported into the main channel and will compensate for the lack of sediment. Furthermore the nourishment material should protect the river bottom of the main channel against erosion, by preventing that the river bottom material washes away. For this, the principle of armouring can be used, explained in appendix C.

Groyne field nourishments will only work against bed degradation in the main channel if suitable material is nourished otherwise the opposite of the aimed effect occurs: enhancement of the bed degradation.

When the material is too coarse, relative to the original bed material, the bed shear stress induced by navigation and the river discharge does not mobilise the sediment. The consequence may be that the dynamic equilibrium in the groyne field changes and the groyne field bottom becomes elevated. The groyne field nourishment is in this case counterproductive.

On the other hand, when too fine material, relative to the original bed material, is added to the groyne field and this sediment is transported to the main channel, the mobility of coarser particles in the main channel bed is increased. This cause an decrease of the equilibrium slope of the bed in the main channel and the bed degradation is enhanced.

When the nourishment material is not properly sorted it could happen that fine grains are transported to the main channel and that the coarse grains stays in the groyne field. It is therefore important that the nourishment material is carefully considered.

The nourishment material is not in the scope of this research, therefore the original bed material is used in the XBeach model. However it should be kept in mind that nourishment material is of great importance.

5.2 Types of nourishments

In this section the choice for three nourishments will be elaborated. The three nourishment are given in figure 5.4. All nourishments are based on the hydrodynamic and morphodynamic processes following from chapter 2 and 3.

Regarding avalanching and terrace formation it is for all three nourishments expected that just after placing, an avalanching process cause the first erosion of the nourishment sides: the sides are to steep and the nourishment material will break loose and fall along the nourishment. The nourishment will get flatter and wider. Thereafter a river-bank-erosion-like process is expected along the sides due to the attack of ship waves and the river discharge.

Furthermore, for all nourishments it is expected that the erosion process of the nourishment is inversely exponential.

At last the left side of the nourishment probably lies within the mixing zone between the main channel and the primary eddy. This may cause extra erosion on the left side of the nourishment and this sediment may flow directly into the main channel.

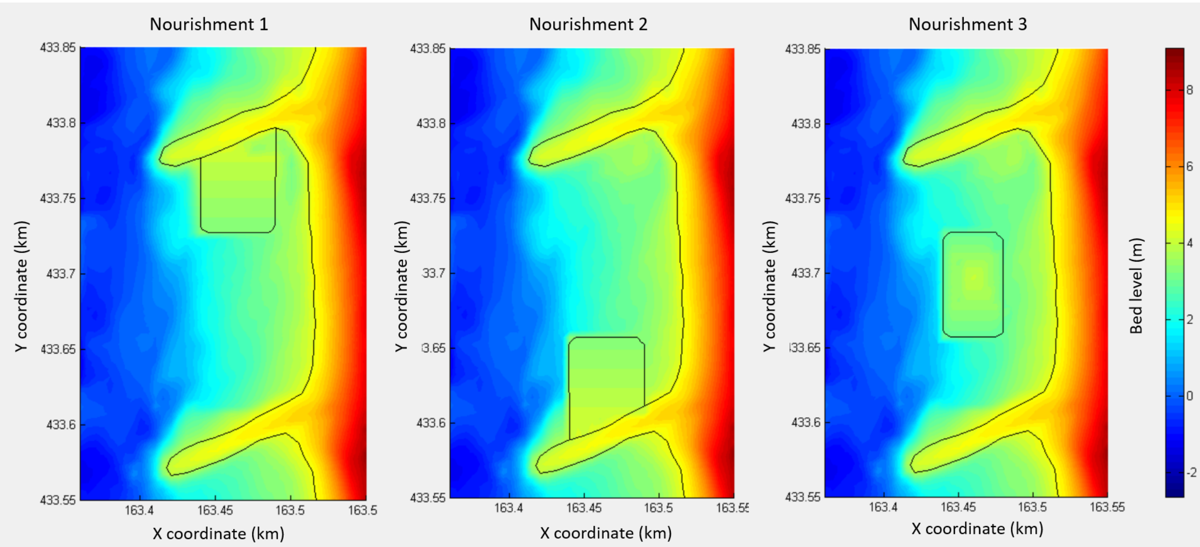


Figure 5.4: Top view of the bed level in case of nourishment 1, 2, and 3.

Nourishment 1

The first nourishment type is sketched in the left panel of figure 5.4. Upstream of the second groyne the material is dumped against the groyne side up to a high of 4.5 m + NAP. The nourishment forms a slope with the top at the groyne side. The bottom of the slope is located about 50 m average from the groyne side and the width of the nourishment is also about 50 m.

Regarding the flow pattern in a groyne field due to river discharge, it is expected that a large part of the nourishment lies within the inflow area of the primary eddy and the interaction area between the secondary and primary eddy. Due to the nourishment the flow area is decreased. It is expected that these three aspects cause erosion along the sides of the nourishment. The eroded sediment may be transported to the main channel by the primary eddy. However the route along the circulating pattern is long and the flow velocity decreases along this path, so probably the transport capacity of the flow will decrease and the sediment is deposited at an other place in the groyne field, for example in the centre.

What also could happen is that the water inflow is blocked by the nourishment and the water will flow into the groyne field more upstream. Then the interaction area will then move upstream. As a results the nourishment will not lie anymore in the turbulent zone(s) in the groyne field and erosion of the nourishment will not or in a lesser extent occur.

Regarding the ship induced water motion it is expected that suction and secondary waves will attack the nourishment. The filling and emptying of the groyne field during and after the passage of a ship cause strong currents (especially along the groynes, river bank and the outflow points at the groyne heads) that, due to the nourishment, have a smaller flow area to flow through. Therefore the flow velocities will increase and higher bed shear stresses are expected around and on top of the nourishment.

The secondary waves may attack the nourishment by wave breaking. This causes entrainment of nourished material that probably will be transport to the main channel by the primary eddy.

Nourishment 2

The second nourishment type is sketched in the centre panel of figure 5.4. Downstream of the first groyne the material is dumped against the groyne side up to a high of 4.5 m + NAP. The nourishment forms a slope with the top at the groyne side. The bottom of the slope is located about 50 m average from the groyne side and the width of the nourishment is also about 50 m. Nourishment 2 is the opposite of nourishment 1.

Regarding the flow pattern in a groyne field due to river discharge, it is expected that a large part of the nourishment lies in the flow area of the primary eddy. Due to the nourishment the flow area is decreased. It is expected that these three aspects cause erosion along the side and on top of the nourishment. The eroded sediment may be transported to the main channel by the primary eddy. For this nourishment the route from the erosion location to the main channel is short. However the flow velocity is already decreased along the primary eddy, so enough transport capacity should be preserved to transport this sediment to the main channel. If this is not the case the flow of the primary eddy is blocked and probably the primary eddy will flow in front of the nourishment to the main channel, as a result the potential erosion of the nourishment will be reduced. Furthermore this nourishment could be beneficial during submerged groynes, middle flow conditions: due to the slope the energy loss at the groyne is less, such that probably the transport capacity will increase and sediment from the top of the nourishment will be eroded and finally transport in the main channel by the mixing layer of the residual large-scale eddies.

Regarding the ship induced water motion it is expected that suction and secondary waves will attack the nourishment in the same way as for nourishment 1.

Nourishment 3

The third nourishment type is sketched in the right panel of figure 5.4. In the middle of the two groynes the the material is dumped as a peaked bump. The top of reaches a level of 4.5 m + Nap. On the four sides of the nourishment a slope is formed from the top to the bottom. The width of the nourishment is about 35 m and the length about 70 m.

Regarding the flow pattern in a groyne field due to river discharge, it is expected that the nourishment lies in the centre, the deposition area, of the primary eddy. The primary eddies flows around the nourishment and can attack all four sides, because the the flow area is decreased. It is expected that these aspects cause erosion along the sides of the nourishment. The eroded sediment may be transported to the main channel by the primary eddy. The route along the circulating pattern depends on the place of erosion. The flow velocity decreases along this path, so probably the transport capacity of the flow will decrease. This may result in that only the downstream part of the nourishment erodes and that this sediment is deposited at an other placed in the groyne field.

What also could happen is the pattern of the primary and the secondary eddy changes into a total different flow pattern. For example an eddy up- and downstream of the nourishment and a flow from the downstream eddy, behind the nourishment, to the upstream eddy. In this situation the flow velocity may stay higher, due to the shorter flow path from and to the main channel, and the transport capacity stay higher and the more sediment is transported to the main channel.

Regarding the ship induced water motion it is expected that again suction and secondary waves will attack the nourishment in the same way as for nourishment 1 and 2. One difference is that all four side of the nourishment are exposed to the ship induced water motion.

5.3 Model results

The purpose of sub-research question 3 it to research how the type of nourishment (shape and location) does influence the way in a nourishment will act as a small feeder nourishment that slowly releases sediment to the main channel. For answering this question the model is used for the three nourishments and the reference situations (base case). In this way the effects of the different nourishments can be assessed. The relevant model output is shown in this paragraph. Extra output can be found in the appendix M, this will be referred to.

Navigation, no river discharge

This run is done to research the effect of ship induced water motion on the behaviour of the nourishment by looking at the flow velocity, the bed shear stress, the sediment concentration and the sediment transport.

Multiple stages during the passage of the ship can be determined in time. The description and the time specification of the stages are as follows:

1. 00:01:30 - 00:02:20: The groyne field is filled by the incoming front wave;
2. 00:02:20 - 00:03:45: The groyne field is emptied by suction due to the water level depression;
3. 00:03:45 - 00:05:30: The stern wave travels into the groyne field and the groyne field is filled by the supply flow;
4. 00:05:30 - : The groyne field is emptied and filled until the equilibrium state is reached again;

The times are given for the centre of the groyne, so this means that when a points lies more up- or downstream of the centre these moments can occur earlier or later.

These four stages (number, time or process) will be referred to during the analysis of the model results.

To get a first idea of the effect of the nourishments on the flow pattern and the flow velocity a look is taken at two types of model output:

- The maximum flow velocities when the water flows from the groyne field in the direction of the main channel (outflow, emptying of groyne field);
- The maximum flow velocities when the water flows from the main channel in the direction of the groyne field (inflow, filling of groyne field);

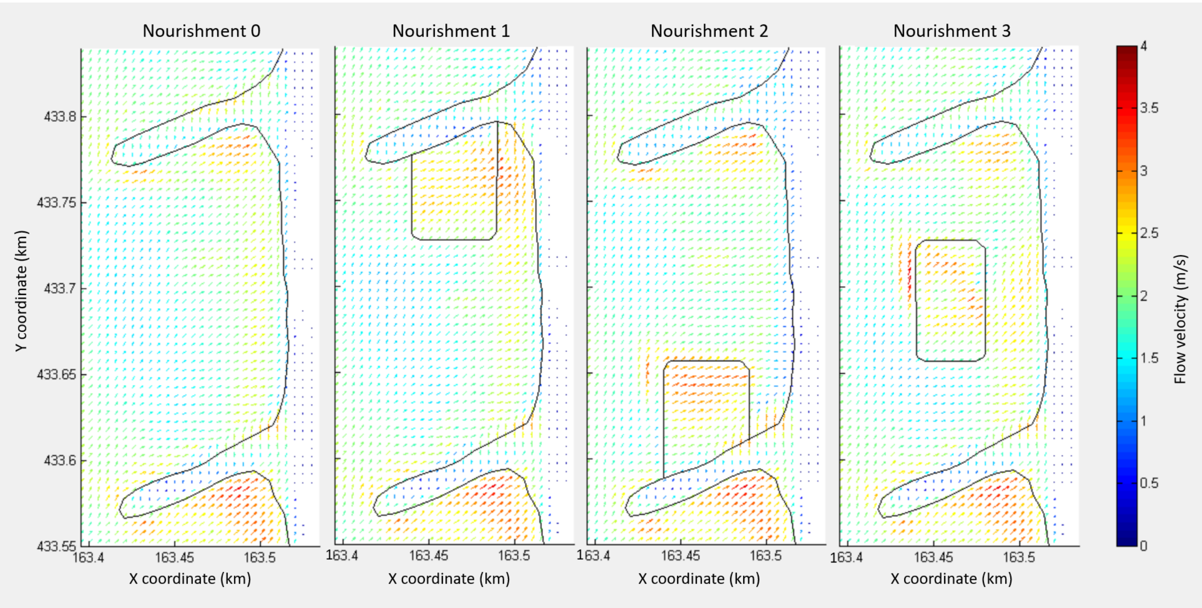


Figure 5.5: Max. Flow velocity when the groyne field is filled during the passage of a ship

In figure 5.5 the maximum inflow flow velocities are given for the reference situation (left panel) and three nourishment. For the situation without nourishment, in the following referred to as nourishment

0, it can be seen that along the river bank and groynes the highest maximum flow velocities develop. This is consistent with literature. Due to the fact that the front waves come in at an angle and travel from upstream to downstream with the ship, the incoming water flows to the most downstream point of the groyne field: the right downstream corner. Therefore high flow velocities develop over there. The location and shape of the nourishments can change these magnitude, direction and pattern of inflow. In the next paragraphs these impact and differences are elaborated for each nourishment.

For nourishment 1 it can be seen that higher flow velocities occur on top and on the right side of the nourishment. Because the ship and its movement through the domain stay constant, it is expected that the same amount of water flows into the groyne field as for the reference situation. Due to the nourishment the flow area gets smaller, this may cause that the flow velocity increase around the nourishment. Because the flow velocity increase is also on top of the nourishment, the water flows over the nourishment when the front wave travels in the groyne field. The flow velocity in the upstream part of the groyne field is more or less the same as for the reference situation.

For nourishment 2 also a flow velocity increase can be seen on top of the nourishment, but more at the downstream edge of the nourishment compared with nourishment 1. The incoming front wave directly comes across the nourishment and flows over the lower part of the nourishment to the downstream right corner. Again the flow area decreases due to the nourishment and therefore the flow velocity increases around and on the nourishment. Because the water still flows to the downstream right corner and the upstream right corner is blocked from inflow by the nourishment, the flow velocity decreases in the upstream right corner. The flow velocity in the downstream part of the groyne field is more or less the same as for the reference situation only along the river bank it seems that the flow velocity decreases a bit.

For nourishment 3 a flow velocity increase can be seen in front (left side) and on top of the nourishment except for the peak that rises above water. The incoming front wave comes across the nourishment in the middle of the groyne field and flows around it to the downstream right corner. Again the flow area decreases due to the nourishment and therefore the flow velocity increases between the nourishment and the riverbank and also around the edges of the nourishment. The flow velocity close to the groynes are more or less the same as for the reference situation.

It appeared that in case of all three nourishments the water flows over the nourishments when the water flows into the groyne field by the front wave. Due to the flow velocity increase on top of the nourishments, entrainment and transport of the nourished material is induced. This process highly corresponds to shoal erosion in coastal area's. When this is the case it is expected that the nourishment will fully erode by the negative feedback process.

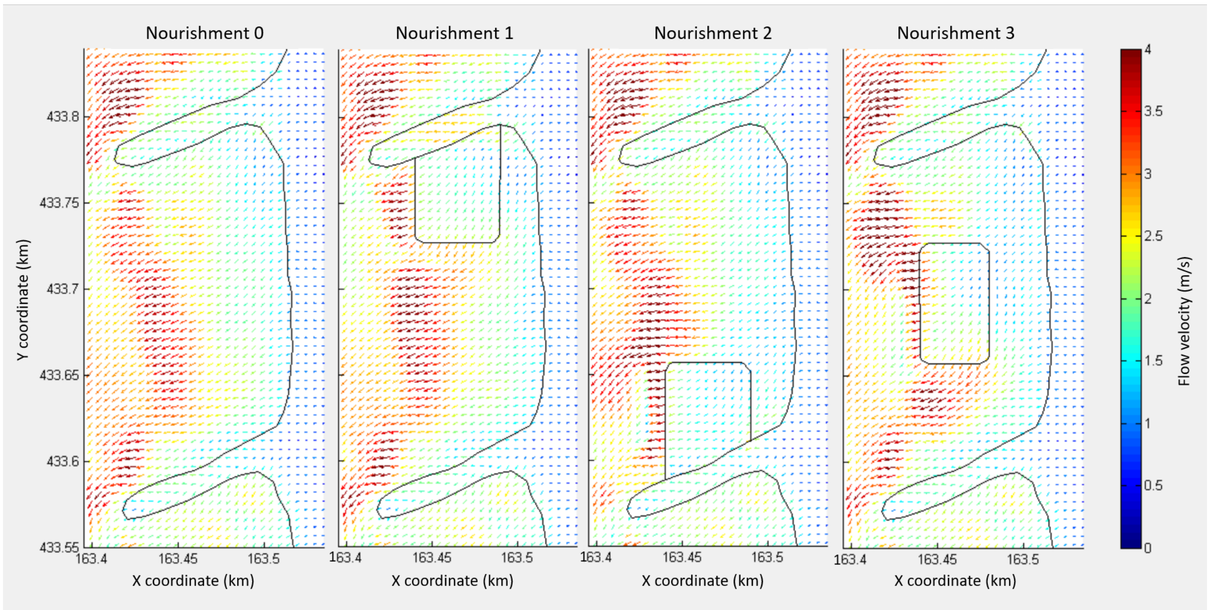


Figure 5.6: Max. Flow velocity when the groyne field is emptied during the passage of a ship

In figure 5.6 the maximum outflow flow velocities are given. For nourishment 0 the high flow velocities occur over almost the full length of the groyne field, close to the main channel. Close to the river bank and the groynes the flow velocities are relative low. Due to suction induced by the water level depression caused by the ship, the water that fills up the water level depression flows out of the groyne field. At the edge of the groyne field the water volume of the whole groyne field flows in a very short time into the direction of the main channel and therefore the flow velocities are high. In the next paragraphs the three nourishment are compared with nourishment 0.

For nourishment 1 the 2/3 upstream part of the groyne field looks almost the same as nourishment 0. At the nourishment and close around it some changes in the flow velocities can be seen. The flow area decreases due to the nourishment and therefore the flow velocity increases around the nourishment. Because the flow velocity on the nourishment does not increase, the water flows mainly around the nourishment to the main channel.

For nourishment 2 the 2/3 downstream part of the groyne field looks almost the same as for nourishment 0. The effect on the flow velocity is comparable to the effect of nourishment 1 on the flow velocity: the flow velocity increases around the nourishment and the water flows mainly around the nourishment to the main channel.

For nourishment 3 the outflow happens on the downstream and upstream side of the nourishment, there the flow velocity increases due to the decrease of flow area by the nourishment. Around the downstream, left and upstream side of the nourishment the flow velocity increases. The water flows around the nourishment, because the flow velocity on top does not increase. When the ship just passes the upstream groyne, the water flows along the upstream side of the nourishment to the main channel and when the ship sails further downstream the water is mainly supplied by a water current downstream of the nourishment.

Because the water flows for all nourishments around the nourishment during suction, stronger currents occur around the nourishments. These flow accelerations attack the sides of the nourishments. This process can be compared with river bank and dune erosion: the nourishment is attacked by currents and the nourishment material break loose and fall along the nourishment. By this observation it may be expected that the nourishment is exposed to erosion by avalanching and the that the material that breaks loose cause the nourishment to get flatter and wider (terrace formation).

Next to the strong currents due to suction also secondary waves contribute to the erosion of the nourishment. This effect of secondary waves cannot be seen in the maximum in- and outflow model results, but should be taken into account. According the literature the secondary waves travel into the groyne field after the ship has passed. The secondary waves attack the nourishment by wave breaking and causes entrainment of nourishment material that probably will be transported to the main channel by the primary eddy.

To get more information when and for how long the maximum in- and outflow velocities occur, multiple points in the groyne field are selected to see the flow velocity fluctuations in time. These points are chosen along the sides of the nourishments where relative high or low flow velocities are found. For nourishment 1 and 2 three points are selected and for nourishment 3 four points. The points between the nourishment and the riverbank are marked red, between the nourishment and the main channel purple and the points that lie on the centre line of the groyne field are marked green (and blue). In the following to specific points will be referred to by their colour. In figure 5.7 the location of these points are given. For each point the flow velocity for no nourishment (nourishment 0) and nourishment 1, 2 and 3 (referred to as nour 0, nour 1, nour 2 and nour 3 respectively) are shown in the graphs.

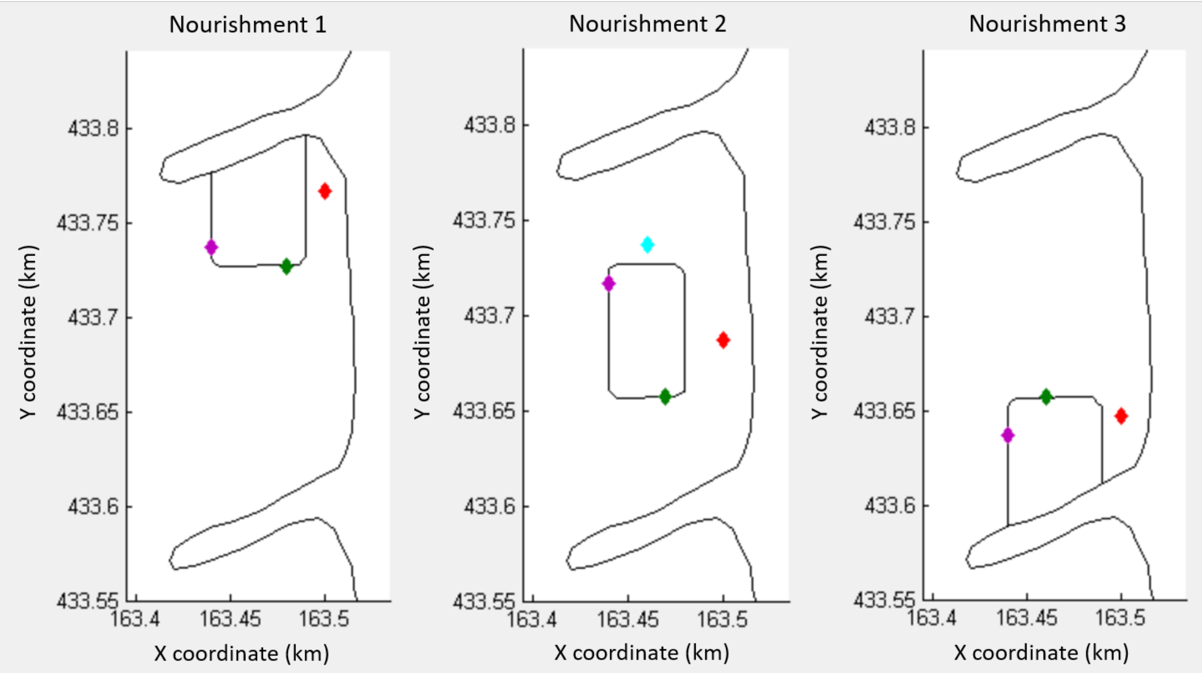


Figure 5.7: Location output points for each nourishment

In the following the flow velocities in time in the case of nourishment 1, 2 or 3 will be compared with the reference situation, the situation that no nourishment is applied (nourishment 0). The flow velocities are negative when water flows from the groyne field in the direction of the main channel (outflow) and when water flows in the opposite direction the flow velocities are positive (inflow). The explanation for the increase or decrease of flow velocities is given in the previous paragraphs, the focus is mainly on the changes in duration of flow velocities.

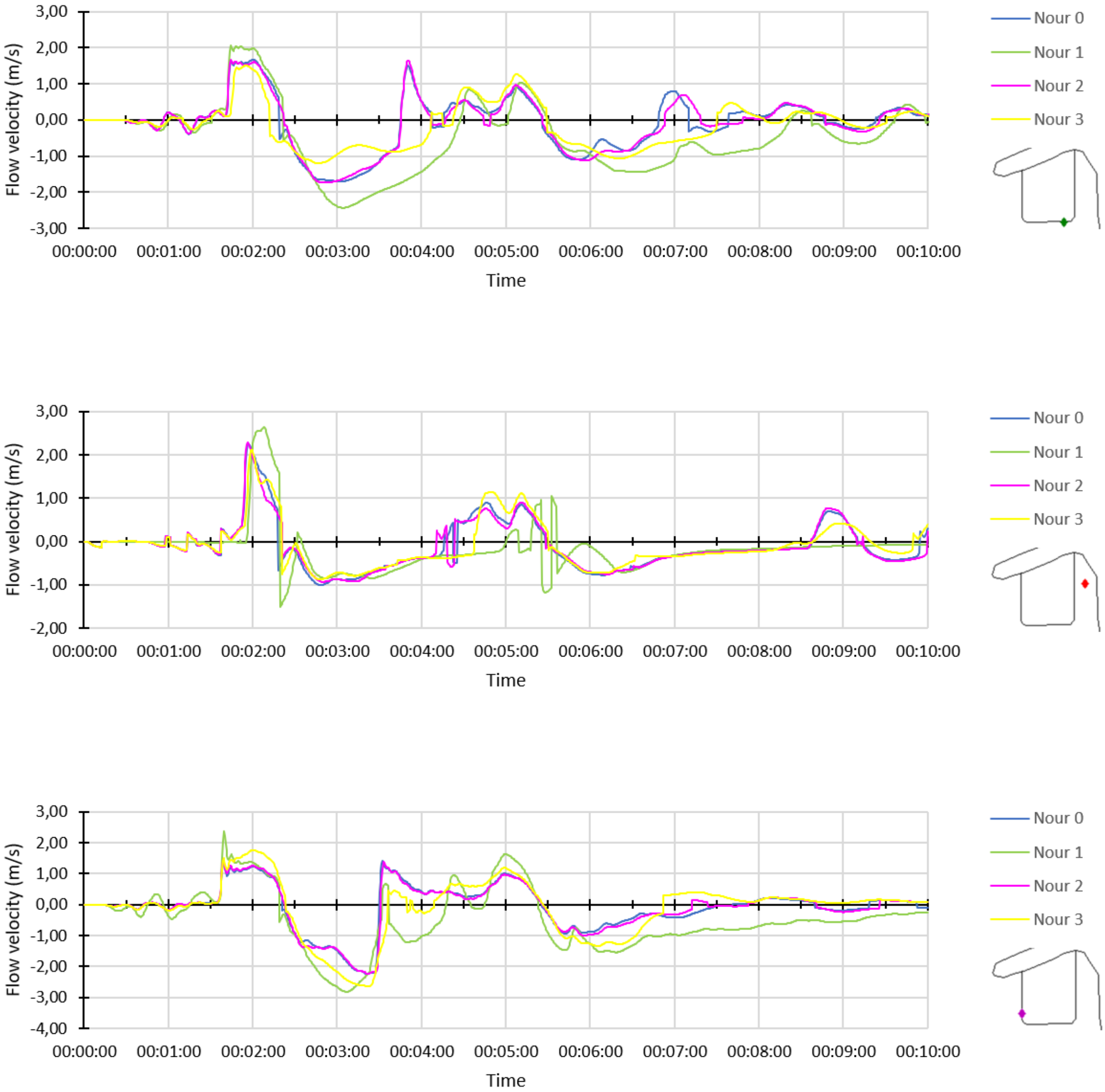


Figure 5.8: Flow velocity nourishment 1

In figure 5.8 the flow velocities are shown at the three points around nourishment 1. Overall it can be seen that when nourishment 1 or nourishment 3 is applied the flow velocities differ from the reference situation at all three locations. Furthermore, the flow velocities that occur when nourishment 2 is applied are practically the same as for nourishment 0 at all three locations.

During stage 1 the flow velocities for nourishment 1 are increasing at all three locations, at the red and green location the flow velocity increases 25%. The duration of the front wave travelling in the groyne field remains unchanged compared to the nourishment 0. When the groyne field is emptied due to suction (stage 2) high flow velocities occur for nourishment 1 at all locations. At green and purple the higher flow velocities hold much longer, because the water needs to flow around the nourishment. At green the flow velocity increases with 0.4 m/s and emptying the groyne field by suction takes about 2 min 20 s instead of 1 min 30 s for the reference situation. During suction sand is transported out of the groyne field, when suction holds longer it is also expected that more sediment is transport out of the groyne field. Therefore it is expected that nourishment 1 will mainly erode at its left and downstream side during suction. For nourishment 3 the flow velocities increase 0.2 m/s at purple and decrease about

1 m/s at green. Due to the decrease in flow velocity at green it takes longer for the water volume to flow to the main channel. In stage 3 the inflow flow velocity is about the same for all nourishments, except for a few fluctuations. These develop because the water depth becomes zero at certain moments. In stage 4 the flow velocities for nourishment 1 at green and purple are larger, but slowly decreases to zero again. At green the same fluctuations as for nourishment 0 are visible, but the outflow predominates for a longer period.

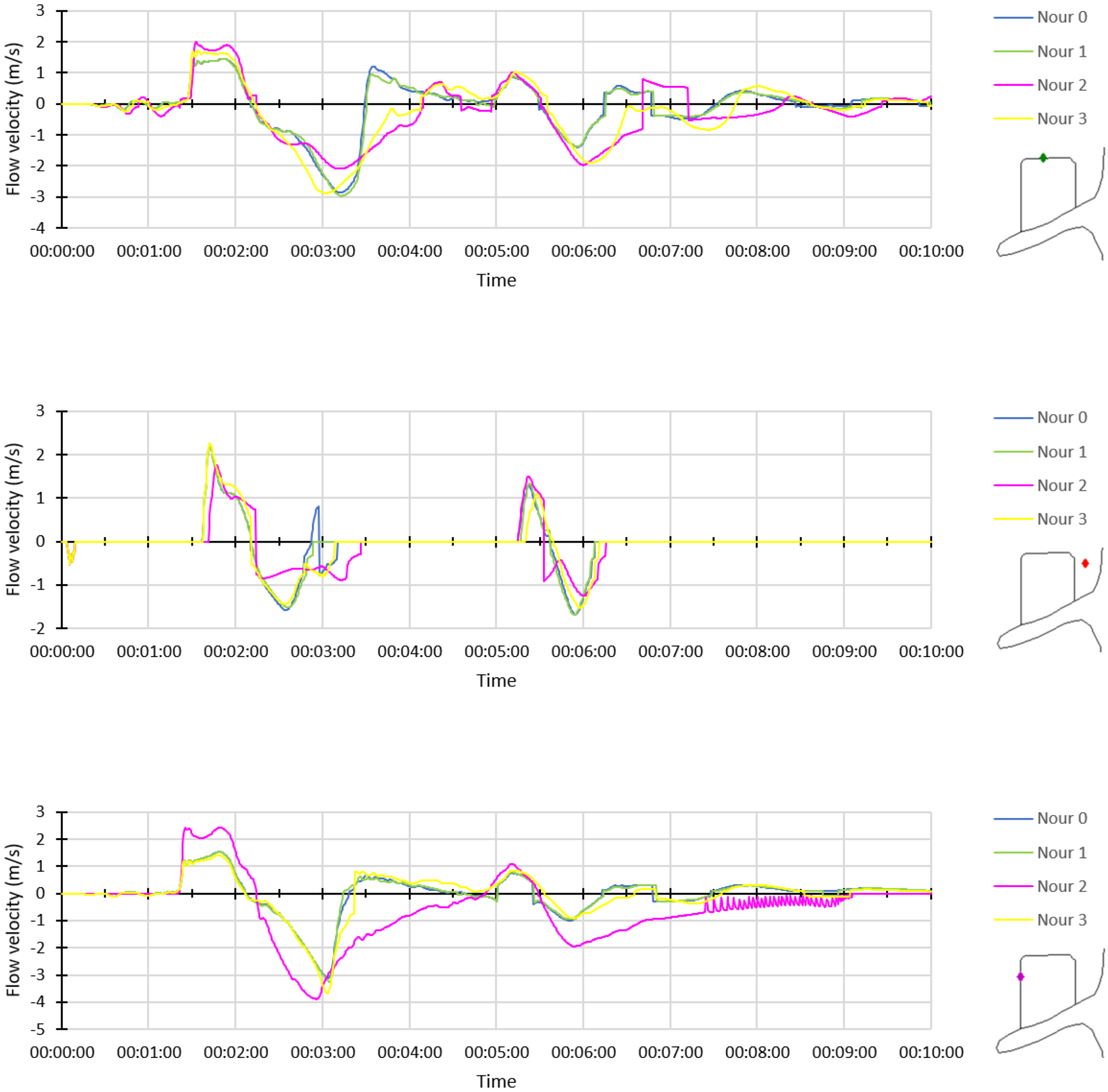
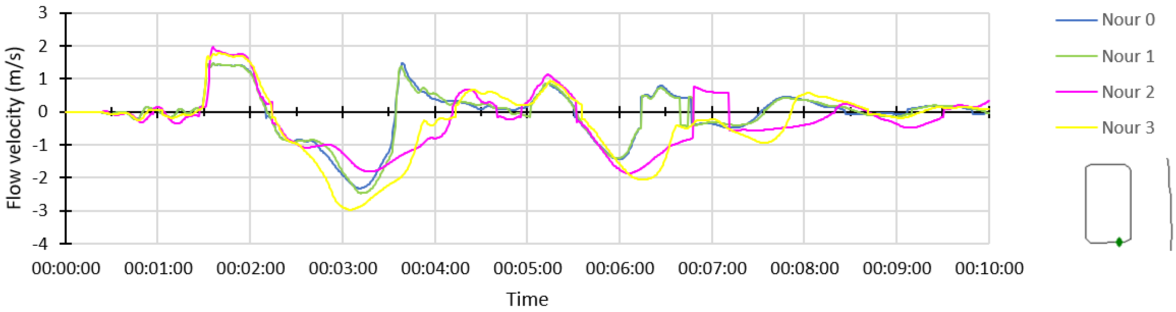
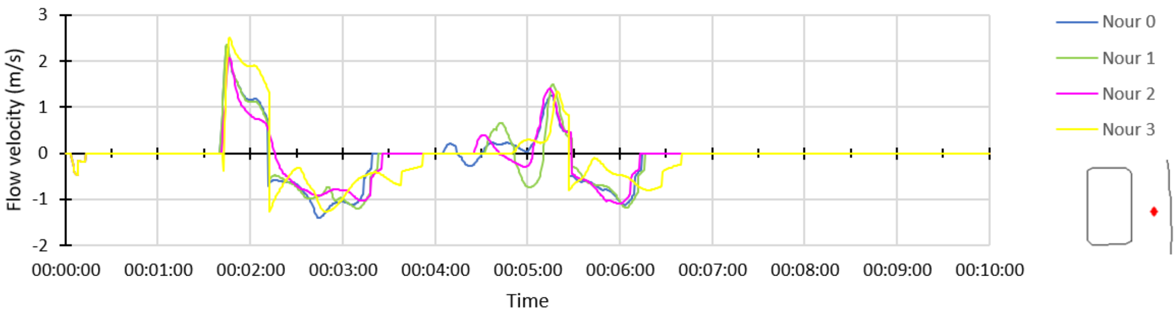


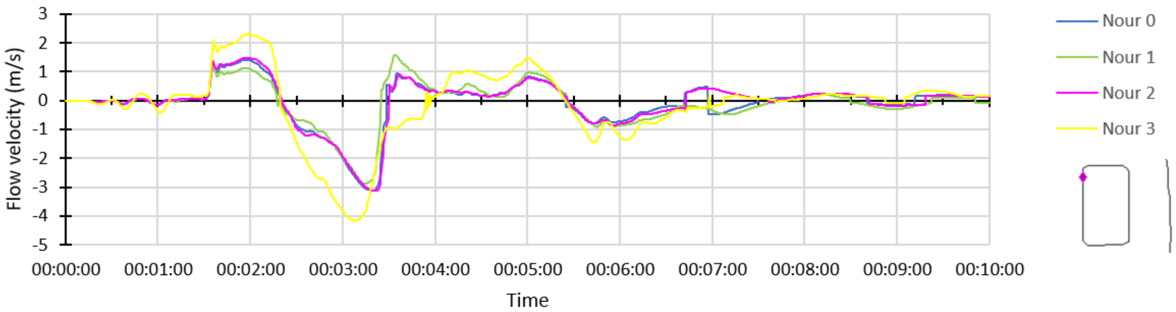
Figure 5.9: Flow velocity nourishment 2

In figure 5.9 the flow velocities are shown at the three points around nourishment 2. It can be seen that when nourishment 2 or nourishment 3 is applied the flow velocities differ from the reference situation at all three locations. Furthermore, the flow velocities that occur when nourishment 1 is applied are practically the same as the flow velocities for nourishment 0 at all three locations.

During stage 1 the flow velocities for nourishment 2 increase at green and purple and decrease at red. At purple the flow velocity increases up to 67%. The duration of the front wave travelling into the groyne field remains the same only at purple the inflow holds about 20 s longer. For nourishment 3 only an increase at green is observed. When the groyne field is emptied due to suction (stage 2) at green and red much lower flow velocities occur for nourishment 2, but these velocities therefore hold longer. At green the flow velocity decreases with 1 m/s, but hold 1 min 10 s longer. At red the flow velocity also decreases with 1 m/s and holds 20 s longer. Only at purple the flow velocities increases (30%) and holds twice as long in case of nourishment 2, because the water needs to flow around the nourishment. Therefore it is expected that nourishment 2 will mainly erode at its left side during suction. For nourishment 3 only at green the flow velocities holds somewhat longer. At the end of stage 3 the inflow flow velocity is about the same for all nourishments. In stage 4 no major difference are found with nourishment 0.







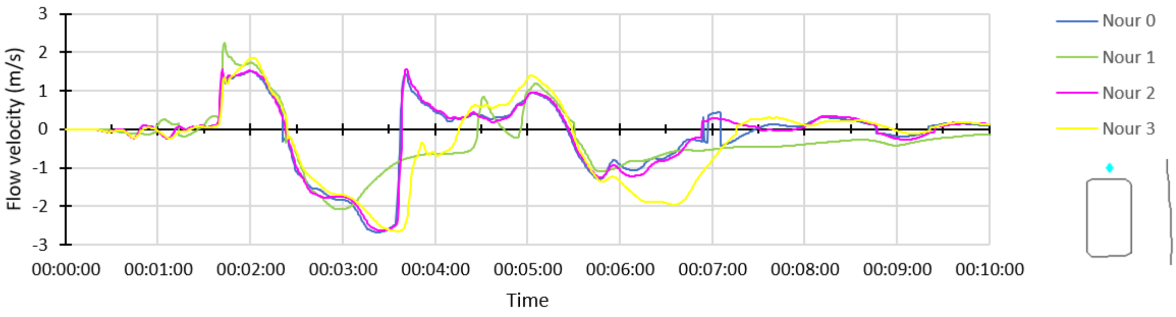


Figure 5.10: Flow velocity nourishment 3

In figure 5.10 the flow velocities are shown at the four point around nourishment 3. Due to nourishment 3 flow velocities in a large part of the groyne field are affected. Although, at green nourishment 1, at red and purple nourishment 1 and 2 and at blue nourishment 2 mainly correspond to the flow velocities for nourishment 0.

During stage 1 the flow velocities for nourishment 3 increase at all locations, especially at red and purple. There the flow velocities increases up to 90 %. The flow velocities for nourishment 1 increase at blue and for nourishment 2 at green. For all nourishments the duration of the front wave travelling into the groyne field does not change. When the groyne field is emptied due to suction (stage 2) at green and purple 0.5 m/s to 1 m/s higher flow velocities occur for nourishment 3, which also hold about 30 s longer. At red and blue the flow velocity only holds a bit longer, but did not increase for nourishment 3. The stronger suction can cause more erosion and sediment transport to the main channel. The same effect occurs again for nourishment 1 and 2 but on the opposite sides of nourishment 3: at green the flow velocities for nourishment 2 decrease and hold longer and at blue the flow velocities for nourishment 1 decrease and hold longer. During stage 3 at purple the flow velocities are a bit higher for nourishment 3, but at the end of stage 3 the flow velocities are about the same for all nourishments. In stage 4 no major difference are found with nourishment 0, only at blue the flow velocities in case of nourishment 1 are mainly directed to the main channel instead.

From these graphs at multiple points it stands out that for nourishment 1 and 2 the water needs to flow a much longer path around the nourishment than for nourishment 3. Therefore the duration of flow velocities for nourishment 1 and 2 differ more from nourishment 0 than when nourishment 3 is applied. Furthermore the largest effects of nourishments are observed during suction, followed by the effect observed when the front wave travels into the groyne field.

A couple of important observations that should be considered in the following of the research are:

- When applying nourishment 1 or 2 the flow velocities and corresponding direction matches with that of the reference situation at the part of the groyne field where the bottom profile is untouched by the nourishment (2/3 upstream or downstream part), so only flow velocities in the area of and close around the nourishment is affected.
- When applying nourishment 3 the flow velocities and corresponding direction changes in almost the whole groyne field in comparison with the reference situation;
- The flow velocity changes of nourishment 1 and 2, mainly 2, are more significant in magnitude and duration than the changes induced by nourishment 3;
- Largest effect of all nourishments are observed during suction followed by the incoming front wave;

The observations done in the flow velocity graphs for the points in the groyne field together with the maximum in- and outflow flow velocities output support the mean flow velocity pattern seen in figure 5.11. This output gives the net flow velocities and direction during the complete passage of the ship.

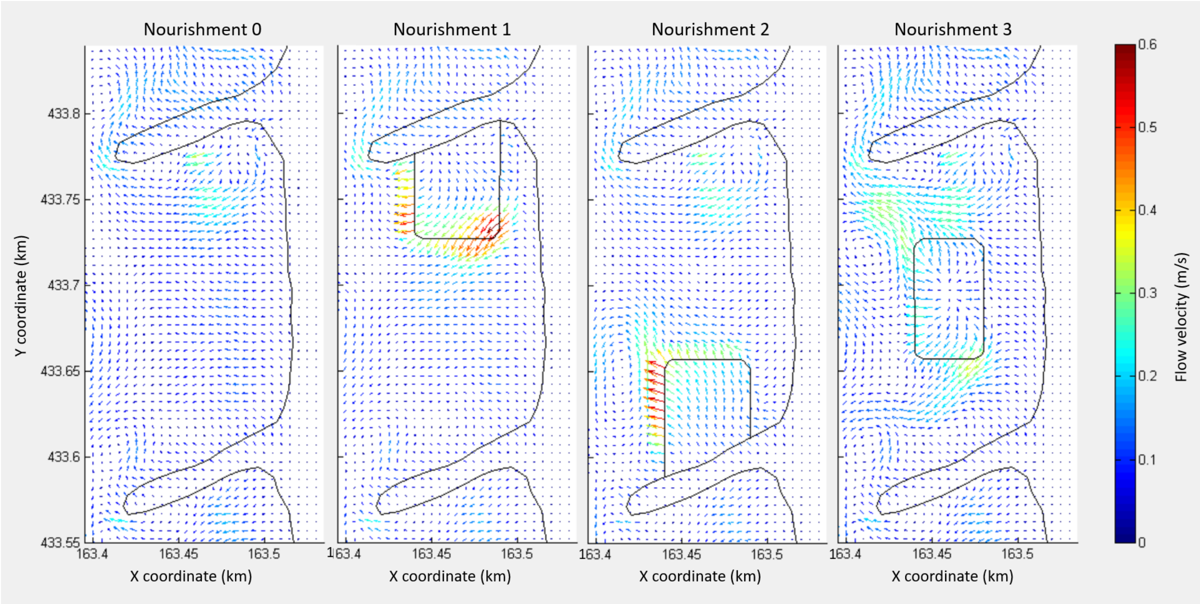


Figure 5.11: Mean. Flow velocity during the passage of a ship

For all four situations the net flow velocity is directed towards the main channel. Furthermore it can be seen that for nourishment 1 and 2 one or two locations along the edge of the nourishment show very high net flow velocities, which is an indication for heavily erosion at these locations. On top and on the right side of these nourishment there is hardly any flow velocity increase. For nourishment 3 the net flow velocity stays lower compared to the other two nourishments, but the area were flow velocity increase occurs is larger: along the downstream, upstream and left side of the nourishment. Meanwhile, also large parts of the original groyne field bottom are subject to the increase flow velocity: mainly upstream and downstream of the nourishment. The flow pattern gives an indication for erosion along the nourishment edges, but also erosion of the groyne field bottom next to the nourishment.

Due to flow velocities bed shear stresses are induced, the model results of the bed shear stress can be found in appendix M.1. The bed shear stress cause sediment entrainment. The sediment concentration (gradient) in the water combined with the flow velocities and corresponding direction cause sediment transport. In the following the sediment transport magnitude in time is given for the same locations as in figure 5.7.

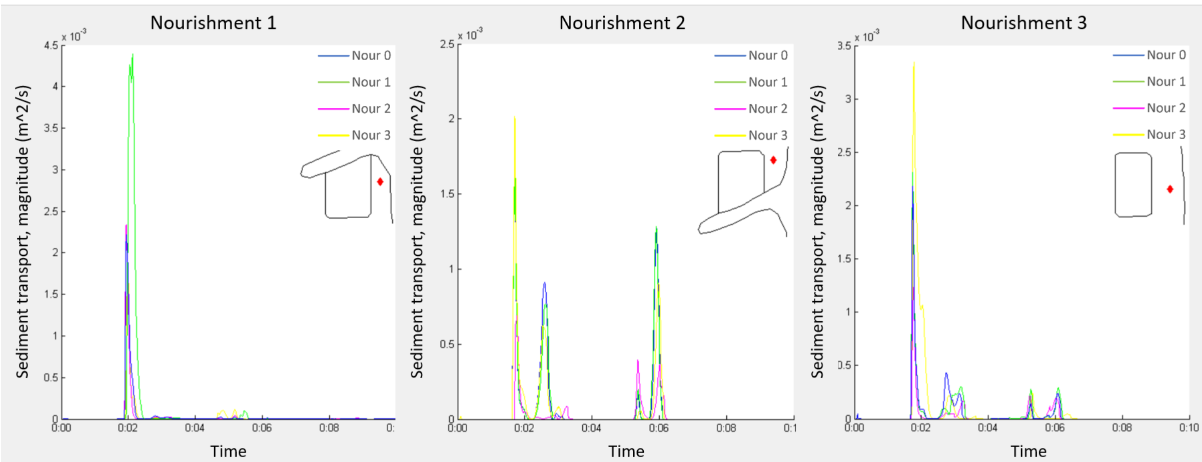


Figure 5.12: Sediment transport close to the riverbank (red locations)

In figure 5.12 the sediment transport magnitude is given for the three nourishments for the red location: point between the riverbank and the nourishment. For this location the highest peaks occur when the front waves travels in, the sediment transport is directed to the riverbank. It can be seen that for nourishment 1 only a large sediment transport peak occurs during the incoming front wave. For nourishment 2 and 3 also peaks occur during suction and when the stern waves travels into the groyne field and the groyne field is filled up again. The red location for nourishment 1 lies closer to the groyne compared to the red location for nourishment 2, and therefore it is less exposed to the strong suction current. This can explain the missing of a sediment transport peak at stage 2 for nourishment 1.

When nourishment 1 is applied the sediment transport during stage 1 increased the most relative to nourishment 0 compared to the other two nourishments, an increase of about 90%. This can be explained by the fact that the front wave travels to the downstream right corner, so a large volume of water is collected in this corner which increases the flow velocities (see figure 5.5), the bed shear stress and sediment transport. Also for nourishment 3 the sediment transport rate increased in stage 1 with 50%, less than for nourishment 1. For both nourishment 1 and 3 only a sediment transport increase occurs during stage 1. Nourishment 2 does not lead to an increase of sediment transport when the front wave travels in. The front wave does not impact the red location of nourishment, as seen before, this explains the small difference with nourishment 0 during stage 1. During stage 2 all three red locations are protected by the corresponding nourishment for the strong suction current, therefore almost no sediment transport occur then.

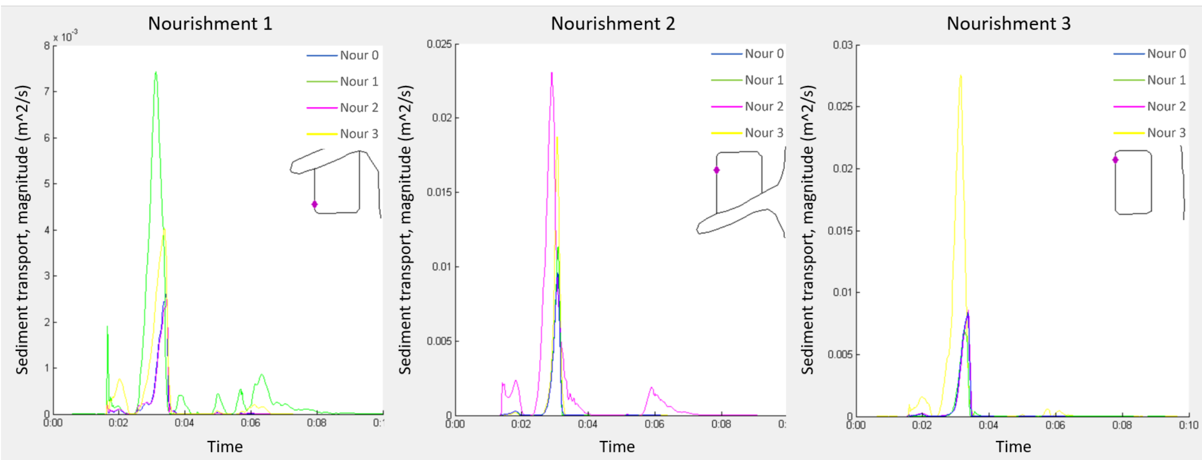


Figure 5.13: Sediment transport close to the main channel (purple locations)

In figure 5.13 the sediment transport magnitude is given for the three nourishments at the purple location: point between the main channel and the nourishment. For all nourishment the highest sediment transport rates occur during suction. For nourishment 1 and 2 also a small peak occurs during the incoming front wave and stern wave, so both waves attack the left side of these nourishments. This is not the case for nourishment 3, probably because the left side slope of the nourishment is less steep. The sediment transport increases for all stages for all nourishments. For nourishment 2 and 3 the sediment transport rates during stage 2 are significantly larger compared to nourishment 1, because the flow velocities are higher and hold longer especially for nourishment 2. The increase relative to nourishment 0 is the largest for nourishment 3, an increase of 0.02 m^2/s.

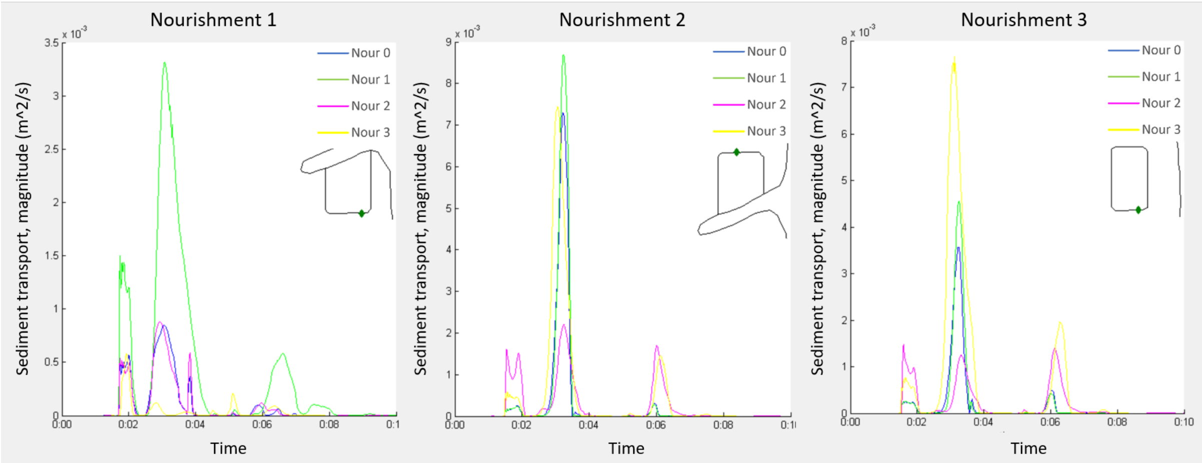


Figure 5.14: Sediment transport in the centre of the groyne field (green locations)

In figure 5.14 the sediment transport magnitude is given for the three nourishment at the green location: in the centre of the groyne field along the edge of the nourishment. Again suction cause the highest sediment transport rates, but for this location more sediment transport does occur during the other stages. The sediment transport increase of nourishment 1, 2 and 3 during the front wave travelling in is now more in line with each other, because the slopes of these nourishment sides have about the same steepness. When the slope of the nourishment side is less steep the attack of the front wave is less effective for the sediment transport. The largest sediment transport increase relative to nourishment 0 occurs for nourishment 1 at all stages, because the front wave travels to the downstream right corner and thereafter this great volume of water flows around the nourishment to the main channel. For nourishment 2 the sediment transport decreases during suction, because due to the nourishment less water flows in the upstream right corner, so during suction less water flows along the green location to the main channel. A couple of important observations of the research are:

- Looking at the output points per nourishment:
  - The highest sediment transport increase relative to nourishment 0 occurs when nourishment 1 is applied, closely followed by nourishment 3. These two nourishments are the most exposed to the attack of the incoming front wave since the front wave travels to the downstream right corner. Thereafter the in the corner collected water volume needs to flow around these nourishment to the main channel again by suction;
  - For nourishment 1 and 3 at all locations a sediment transport increase relative to nourishment 0 occurs;
  - For nourishment 2 only at the left side of the nourishment a sediment transport increase relative to nourishment 0 occurs, at the other two point the sediment transport decreases. Due to the nourishment less water flows to the upstream right corner during the incoming front wave, therefore a relative weak suction currents flows around the nourishment;
  - The slope of the nourishment edge influences the impact of the front wave. When the slope is relative steep the attack by the front wave is more effective in eroding sediment from the nourishment;
- Looking at the whole groyne field: for all three nourishment the front wave attacks multiple locations at the nourishments, but only for nourishment 1 and 3 suction is effective in transporting sediment in the direction of the main channel at multiple locations;
  - Number of points of a total of 9 were sediment transport increase relative to nourishment 0 during incoming front waves:
    - Nour 1: 5

  * Nour 2: 5
  * Nour 3: 4
- Number of points of a total of 9 were sediment transport increase relative to nourishment 0 during suction:
  * Nour 1: 5
  * Nour 2: 1
  * Nour 3: 5

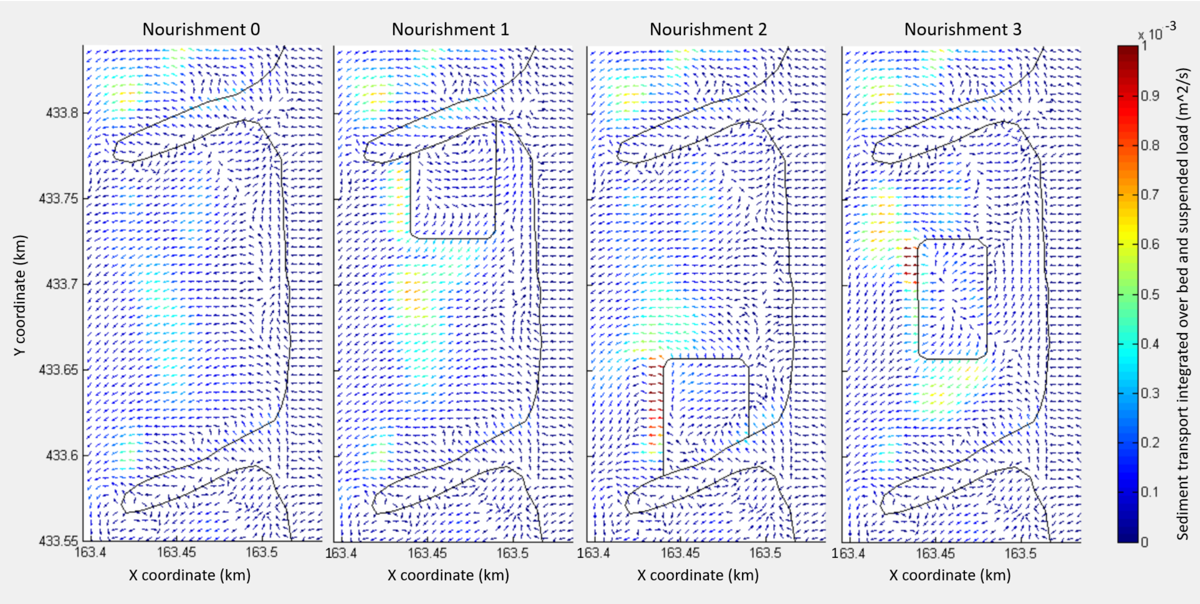


Figure 5.15: Mean sediment transport during the passage of a ship

In figure 5.15 the net sediment transport during the passage of the ship is given for the four situation. The aim of placing a nourishment in the groyne field is that its material will be transported to the main channel. When the front wave comes in the sediment can be brought already in suspension and transported in the direction of the river bank quickly followed by the suction current that transports the already entrained sediment to the main channel, but also brings extra sediment in suspension and transports that to the main channel. For all three nourishment the front wave attacks multiple locations at the nourishments, but only for nourishment 1 and 3 suction is effective in transporting sediment in the direction of the main channel at multiple locations.

When the secondary waves travel under about the same angle into the groyne as the front wave it may be expected that the attack of the secondary waves has the largest impact on nourishment 1 or nourishment 3. This depends on the impact of these nourishments on the eddy pattern in the groyne field due to river discharge, since these eddy circulation may transport the, by secondary waves suspended, sediment particles to the main channel.

Furthermore from figure 5.15 follows that the erosion of the nourishment by the influence of navigation mainly occurs at the sides instead of on top of the nourishment, like river bank erosion. Therefore it can be expected that the nourishment will get exposed to extra erosion by avalanching, such that the material breaks loose and fall along the nourishment. The nourishment will first get, during its erosion process, wider and flatter.

Low river discharge, no navigation

This run is done to research the impact of normal flow conditions during a period of low river discharge (66 days per year the river discharge is lower) without disturbance of ships on the behaviour of the nourishment. For this, the flow velocity, bed shear stress and the sediment transport model output are looked at.

In figure 5.16 and figure 5.17 the flow velocity for the four scenario's are shown. This gives information about how the flow pattern may change in the groyne field and in what direction the sediment will be transported when it is eroded at a certain part of the nourishment.

For nourishment 0 (no nourishment) the expected flow pattern of two large-scale eddies, the primary and the secondary, can be seen. In the 2/3 upstream part of the groyne field the primary eddy circulates and in the right downstream corner a smaller secondary eddy circulates. At both groyne heads water flows out of the groyne field.

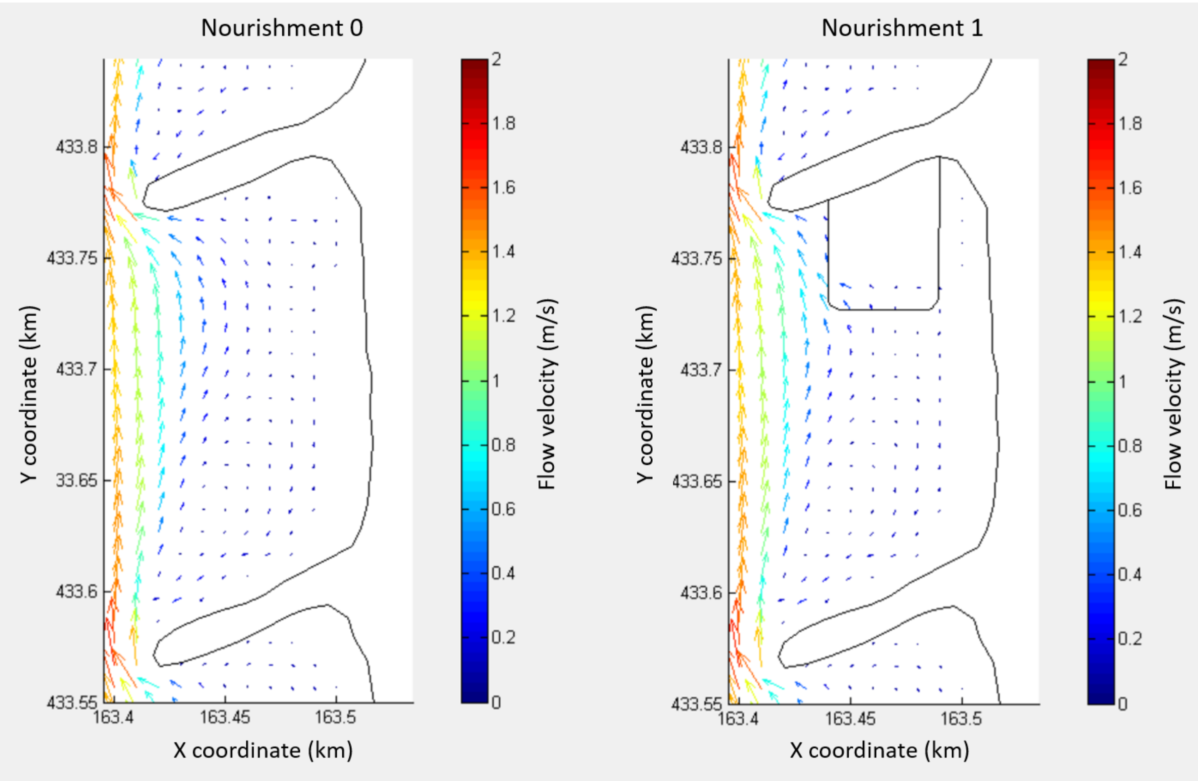


Figure 5.16: Flow velocity in case of low flow conditions

In case of nourishment 1 it can be seen that the primary eddy stays unchanged, the water inflow is not blocked. The secondary eddy almost disappears, only a small circulation can be found at the right upstream corner of the nourishment. Almost no water flow is present between the nourishment and the river bank.

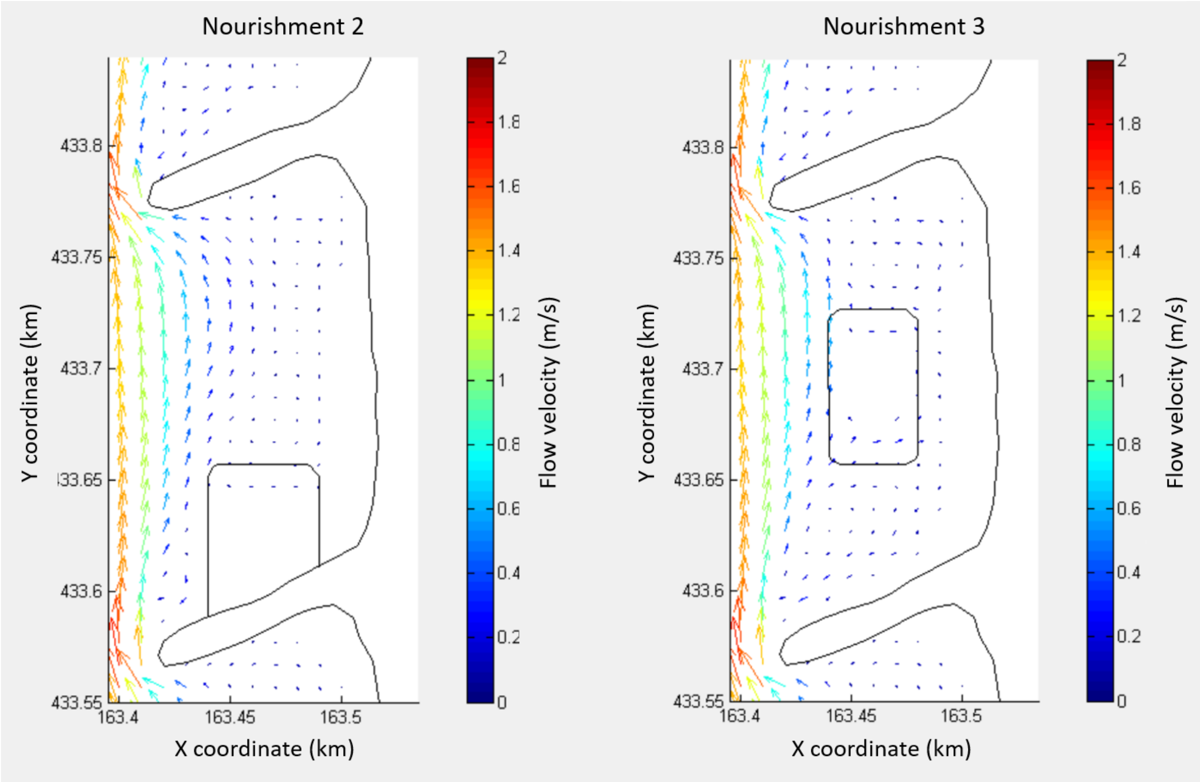


Figure 5.17: Flow velocity in case of low flow conditions

For nourishment 2 the inflow of water from the main channel and the secondary eddy remain unchanged. The outflow of the primary eddy to the main channel seems to be blocked and now found a new path in front of the nourishment to the main channel. Again no water flow is found between the river bank and the nourishment. At last a new small eddy is formed at the left side of the nourishment.

The flow pattern in case of nourishment 3 changed significantly. Upstream and downstream of the nourishment two, almost equal in size, eddies developed. On the right side of the nourishment water flow from the downstream eddy to the upstream eddy. So it looks like there is one large eddy around the nourishment and two smaller eddies.

The bed shear stress follows the pattern from the flow velocity, the bed shear stress output of the model for only river discharge for all four scenario's can be found in appendix M.2.

To get more insight in the actual flow velocities and the bed shear stresses are given in figure 5.19 for the same output locations as used before. The location of these output points is repeated in figure 5.18. The nourishment that is yellow marked is the nourishment around which the coloured dots lie.

When looking at the flow velocities at the red locations, only for nourishment 2 and 3 water flow is observed at the most downstream red locations, since there the secondary eddy circulates. Nourishment 1 blocks this circulation of the secondary eddy. The highest flow velocities occur at the purple locations. These locations lie within the mixing layer between the main flow and the primary eddy in the groyne field. For nourishment 2 no water flow is observed at the purple location, this is because the output point is located to close to the nourishment.

Furthermore, nourishment 3 has the largest impact on the flow velocity in the groyne field compared to the reference situations: at two locations in the groyne field the flow velocity increases and for nourishment 1 and 2 only at one locations the flow velocity increases. In additions it can be seen that for nourishment 1 and nourishment 2 the up- and downstream part, respectively, remain unchanged compared to the reference situation.

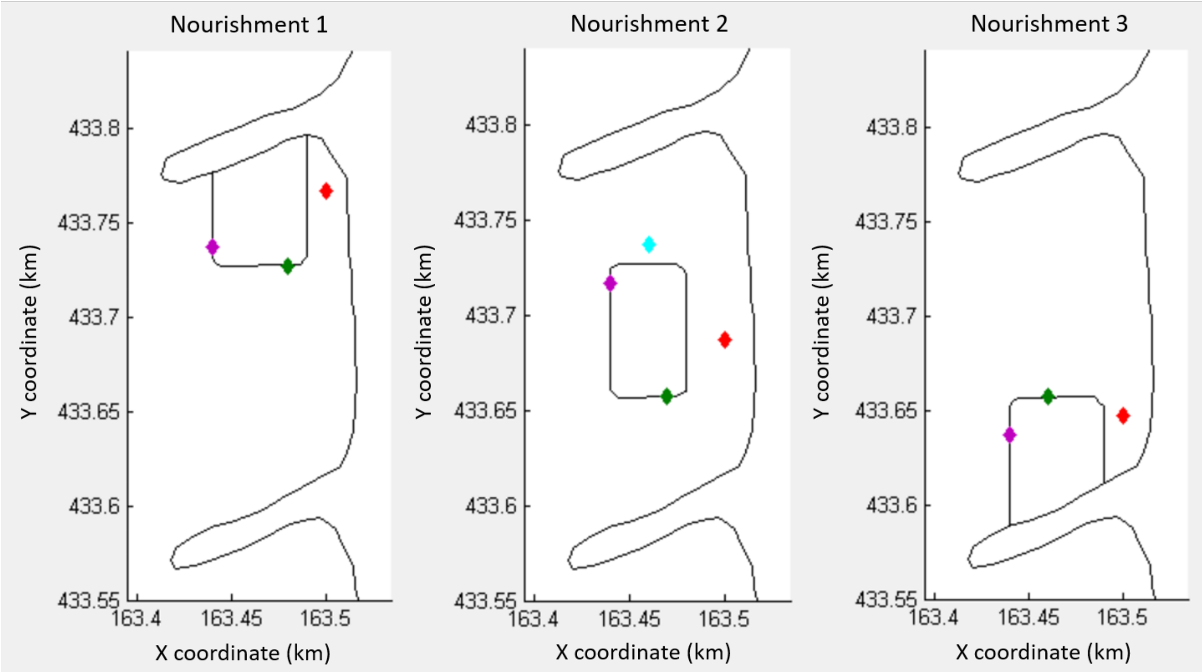


Figure 5.18: Location output points for each nourishment

		Flow velocity (m/s)					Bed shear stress (N/m^2)			
		Red •	Green •	Purple •	Blue •		Red •	Green •	Purple •	Blue •
Left panel in figure 5.18	Nour 0	0.028	0.029	0.410		Nour 0	0.000	0.008	0.493	
	Nour 1	0.000	0.012	0.642		Nour 1	0.000	0.002	1.337	
	Nour 2	0.027	0.028	0.412		Nour 2	0.000	0.005	0.491	
	Nour 3	0.016	0.133	0.395		Nour 3	0.000	0.026	0.232	
Middle panel in figure 5.18	Nour 0	0.000	0.068	0.035		Nour 0	0.000	0.012	0.008	
	Nour 1	0.000	0.067	0.029		Nour 1	0.000	0.012	0.006	
	Nour 2	0.000	0.095	0.000		Nour 2	0.000	0.040	0.000	
	Nour 3	0.000	0.155	0.065		Nour 3	0.000	0.085	0.014	
Right panel in figure 5.18	Nour 0	0.000	0.096	0.418	0.190	Nour 0	0.000	0.022	0.623	0.114
	Nour 1	0.000	0.100	0.481	0.137	Nour 1	0.000	0.024	1.161	0.000
	Nour 2	0.000	0.111	0.419	0.189	Nour 2	0.000	0.043	0.623	0.113
	Nour 3	0.000	0.114	0.609	0.104	Nour 3	0.000	0.042	1.186	0.031

Figure 5.19: Flow velocities and bed shear stresses at output points

When looking at the bed shear stresses at the output points qualitative the same observations can be done as for the flow velocities. Furthermore it can be seen that all the bed shear stresses remain below the critical bed shear stress of 1.30 N/m^2 for the original bed material in the Waal at the research location (see section 4.5 for calculation for sediment particle with a grain size of 2 mm).

Overall it can be seen that the highest flow velocities and bed shear stresses occur in the mixing layer between the main flow and the flow in the groyne field.

When considering the sediment concentration output of the four scenario's (appendix M.2), it becomes clear that only for nourishment 1 and 3 around output location purple a non zero sediment concentration is observed, still very low sediment concentrations. Probably the smaller parts of the bed material are brought in suspension by the changed water flow in the groyne field in case of nourishment 1 and 3. At the same locations the highest bed shear stresses are observed in the table of figure 5.19.

Lastly, the results of the sediment transport (appendix M.2) correspond to the previous observations: in the case of no nourishment and nourishment 2 no sediment transport in any direction is found in the groyne field. For nourishment 1 and 3 at the same locations as were the sediment concentrations become non zero a very small sediment transport is observed in about the same direction as the flow velocity. For all four situation at the mixing layer area a sediment transport from the main channel to the groyne field can be seen, this corresponds to the literature, this transport at the edge of the groyne field is not affected by the nourishment.

Middle river discharge, no navigation

This run is done to research the impact of normal flow conditions during a period of middle river discharge (66 days per year the river discharge is lower) without disturbance of ships on the behaviour of the nourishment. For this, the flow velocity (magnitude and direction) and sediment transport (magnitude and direction) model output are looked at.

In figure 5.20 and figure 5.21 the flow velocity and corresponding direction for the four scenario's are shown. This gives information about how the flow pattern may change in the groyne field and in what direction the sediment will be transported when it is eroded at a certain part of the nourishment.

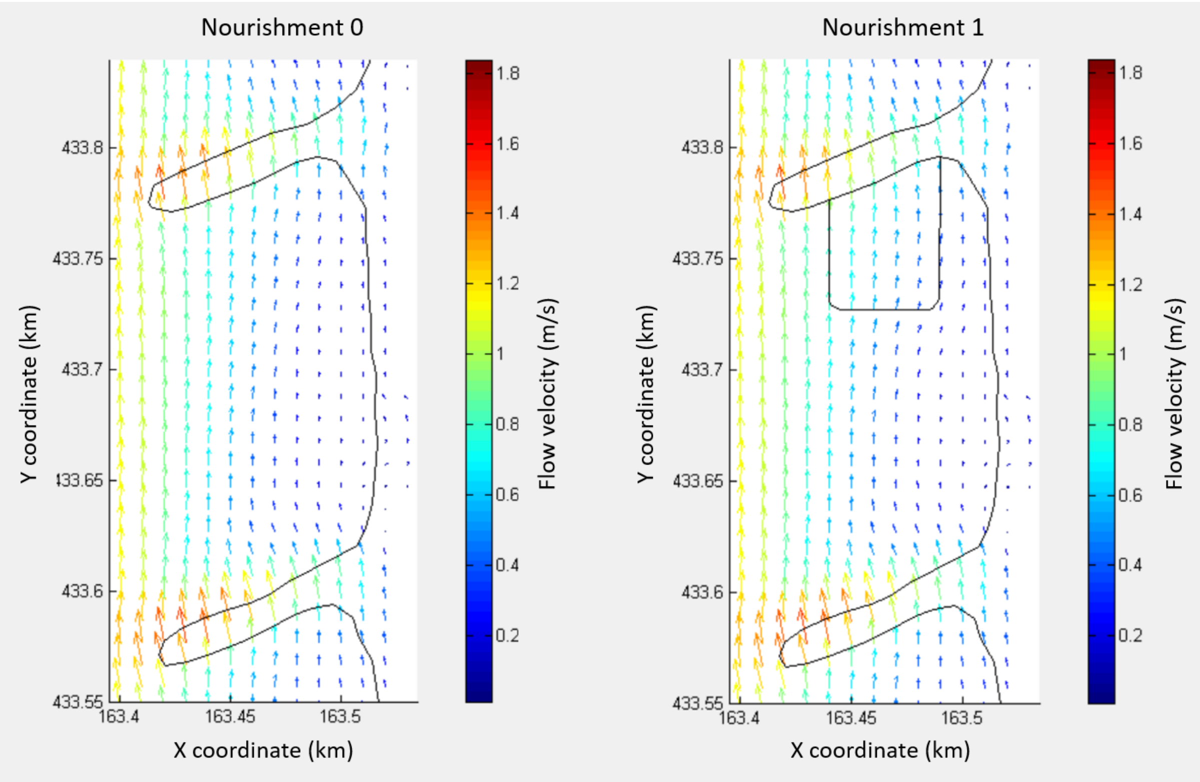


Figure 5.20: Flow velocity in case of middle flow conditions

For nourishment 0 (no nourishment) the expected flow pattern of unidirectional flow over the groynes and large-scale eddies can be seen.

In case of nourishment 1 it can be seen that the flow pattern stays mainly unchanged: the 2/3 upstream part of the groyne field. The flow velocity on the nourishment increases, due to the presence of the nourishment. The nourishment leads to an more gradual flow line over the groyne. Also between the nourishment and the river bank the flow velocity increases, since the flow area decreases by the nourishment.

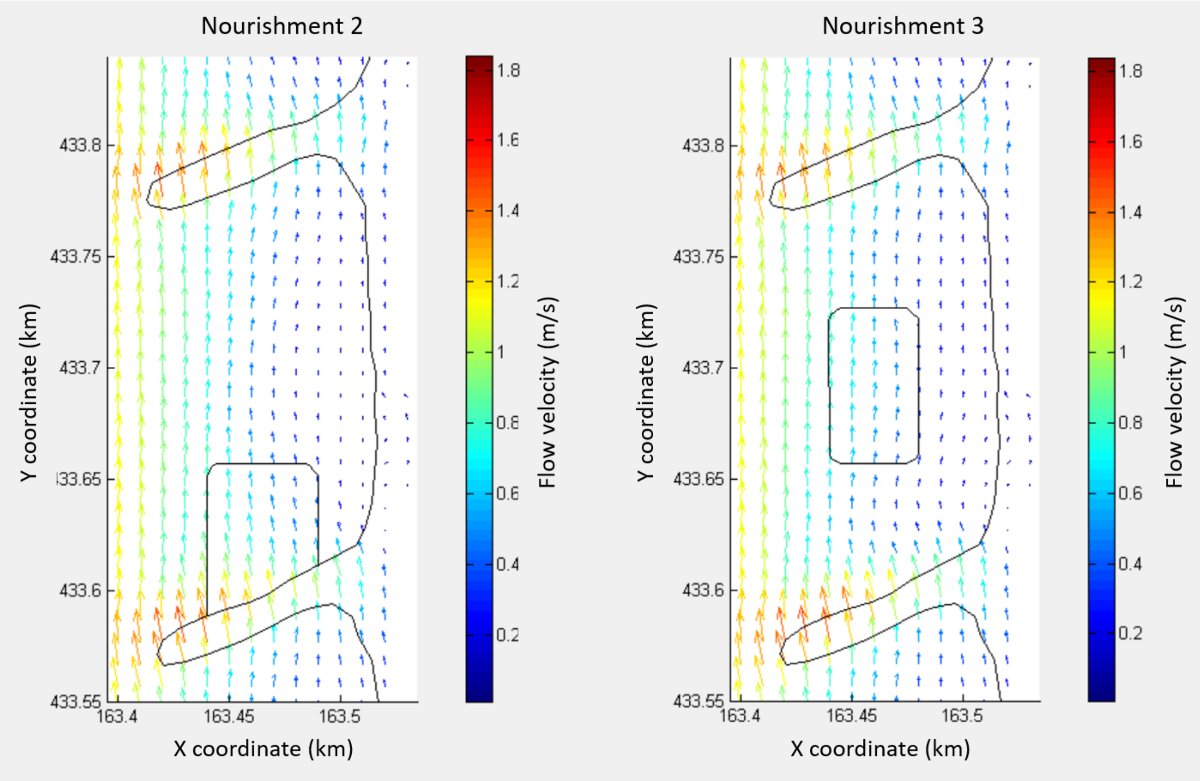


Figure 5.21: Flow velocity in case of middle flow conditions

For nourishment 2 the 2/3 downstream part of the groyne field remains unchanged. The circulation path of the eddy is decreased and the flow velocity of the circulation also. The nourishment partly blocks the eddy. The flow velocity on top of the nourishment increased due to presence of the nourishment. The nourishment leads to a more gradual flow line over the groyne.

The flow pattern in case of nourishment 3 changed in the centre of the groyne field. The eddy circulation path is smaller due to the blockage of the nourishment, but the flow velocity of the eddy is higher. The flow velocity on top of the nourishment increases, since the flow area decreases. The nourishment causes a flow velocity increase in almost the whole groyne field.

Since the flow velocity changes are minor it is expected that almost no to zero extra sediment transport is induced by the nourishments. The sediment transport output of the model for only middle river discharge for all four scenario's can be found in appendix M.3.

The results of the sediment transport correspond to the previous observations: at the locations on top of the nourishment, where the flow velocity increases, sediment transport occurs. For nourishment 2 in the direction as the water flows. For nourishment 1 and 3 the sediment transport is in any direction. In addition, the sediment transport rates in the groyne field are very small for all three nourishments, almost zero.

5.4 Evaluation

For sub-research question 3 a model is used to get more insight in how the location and shape of a nourishment influence the way a nourishment act as feeder nourishment. The model is run for navigation without river discharge, for no navigation with low river discharge and for no navigation with middle river discharge. For the first two runs the low water level was applied and for the third run the middle water level.

From the model results of the model run of navigation without river discharge during low water appeared that for the three tested groyne field nourishments types the net sediment transport is directed to the main channel, which corresponds with the aim of placing the nourishment.

In general, it was found that the front wave, travelling into the groyne field, mobilises already some sediment of the nourishment and transports in the direction of the river bank. This process is directly followed by the strong suction current due to the water level depression induced by the passing ship. This suction current, directed to the main channel, is relatively strong and therefore mobilises much more sediment along the edges of the nourishments. The total amount of mobilised sediment by the front wave and the suction current is transported in the direction of the main channel by the suction current. The stern wave also mobilises sediment, that somewhat later is transported in the direction of the main channel, but this is much less than the sediment transport induced by suction. Therefore suction is the driving factor for sediment transport from the nourishment to the main channel.

The effect of the secondary waves cannot be seen in the model results. According to the literature these waves travel into the groyne field after the ship has passed and attack the groyne field nourishment as well and bring sediment in suspension.

The combination of waves and currents induced by navigation attack the nourishment mainly at the edges of the nourishments. This process can be compared with river bank erosion, therefore it can be expected that the nourishment get exposed to extra erosion by avalanching. Material of the nourishment will break loose and fall along the nourishment, the nourishment gets flatter and wider. In the end the nourishment will fully erode by a negative feedback process, the same principle as for shoals on coastal beaches.

More specific, when applying a nourishment attached to the up- or downstream groyne, the sediment transport matches with that of the reference situations at the part of the groyne field where the bottom profile is untouched by the nourishment (2/3 upstream or downstream part). So only in the area of and close around the nourishment extra sediment transport is observed. Distinguishing between the up- and downstream nourishment attached to the groyne: for the nourishment that is located downstream the sediment transport rates on and close to the nourishment are higher than when the same nourishment is located in the upstream part of the groyne field. This is because the front wave travels to the downstream right corner of the groyne field, therefore the wave attack is larger on the downstream than upstream nourishment. In addition, by suction the large water volume that was collected in the right downstream corner needs to flow around the downstream nourishment to the main channel. Because this water volume is larger than the water volume that flows from the upstream right corner to the main channel in case of the upstream nourishment, larger sediment transport rates are induced on a larger area for the downstream nourishment.

A nourishment placed in the centre of the groyne field has a different effect than the nourishments up- and downstream attached to the groyne. A centre nourishment causes a relative less sediment increase, but this increase occurs at the up-, downstream and left edge, but also further away from the nourishment on the up- and downstream side of the nourishment. The outflow due to suction is forced to split up into smaller stronger currents by the centre nourishment. So no side of a centre nourishment is protected from waves and currents.

From the model results of the model run of low river discharge without navigation appeared that in general the flow pattern in the groyne field induced by the river discharge is affected by a nourishment. But the effect of a nourishment is not such that the flow velocity of the primary eddy increase enough to mobilise sediment at any location in the groyne field. Still the large-scale eddies in a groyne can transport already mobilised sediment by secondary waves to the main channel.

More specific, for a nourishment located downstream attached to the groyne the inflow of water by the river discharge is not blocked by the nourishment. For a nourishment located upstream attached to the groyne the outflow of water by the primary eddy is blocked by the nourishment. Furthermore the flow velocities in the primary eddy in the groyne field stays higher in case of a nourishment located downstream than for a nourishment located upstream. Therefore it is more likely for the downstream nourishment that already suspended sediment is transported to the main channel than for the upstream nourishment.

For the centre nourishment the primary eddy is cut up into two eddies, one downstream and one upstream of the nourishment. The paths of the eroded sediment from the nourishments to the main channel get shorter and the flow velocities do not change. Therefore more suspended sediment is expected to be transported to the main channel compared to the upstream and downstream nourishments.

From the model results of the model run of middle river discharge without navigation appeared that in general the flow pattern in the groyne field induced by the river discharge is hardly affected by a nourishment. Therefore almost no extra sediment is mobilised at any location in the groyne field, only on top of the nourishment very little sediment transport increase was found for all three nourishments.

From the first run (navigation) it appeared that the downstream nourishment and the centre nourishment have the highest potential to function as small feeder nourishment. From the second run (low river discharge) it appeared that the flow pattern in case of the centre nourishment has changed most favourably for sediment transport to the main channel. From the third run (middle river discharge) it appeared that the flow pattern for all three nourishment does not significantly changed.

In terms of the shape of the nourishment it can be said that to maximise the effect of the negative feedback process the top of the nourishment should be below the low water level. Furthermore the steepest edges of the nourishments erode the fastest by avalanching but also by the currents. Based on the above, a submerged nourishment with steep edges in the centre of the groyne field is advised.

6. Discussion

The objective for this research was to deepen insights how groyne field nourishments can act as small feeder nourishments that release sediment slowly and thus compensate locally for shortage of sediment supply in rivers with large scale bed degradation. For this research a literature study and a simulation model are used.

In this chapter some discussion points are highlighted which should be taken into account when further research will be done or when the results of this research are used for future purposes.

From the model validation appeared that XBeach can simulate the primary waves, but the simulation of secondary waves during low and middle flow conditions is unclear. From the literature was obtained that secondary waves should be visible in the model results of XBeach with a grid of 5 m x 5 m. Nevertheless the secondary waves were only clearly visible in the main channel, in the groyne field the secondary waves were almost fully damped. These model results were in line with the visual observation, but not with the literature where it is stated that secondary waves hardly damp. As a possible explanation for this damping the turbulent water movement in the mixing layer together with the steep slope between the main channel and the groyne field can be given. In addition, a numerical explanations can be that the grid is still to coarse. This can be the case since for simulating bed update in XBeach in the non-hydrostatic mode a grid size of less than 1 m is required.

The sediment transport rates in the model are calculated for the original bed material in the groyne field. It should be kept in mind that probably coarser nourishment material is needed to enhance armouring of the bed of the main channel. When this is the case less sediment will get in motion by navigation and the effect of a groyne field nourishment is diminished. But when the nourished material is too coarse the grains will not get mobilised at all by the the effect of navigation and the river discharge, the dynamic equilibrium in the groyne field may change and a groyne field nourishment does not work as feeder nourishment.

In the current model ships travel downstream along groyne fields situated on the northern side of the Waal. It is expected that when ships travel upstream, along groyne fields situated on the southern side of the Waal, the effect of navigation causes higher flow velocities in the groyne field and increases the sediment transport out of the groyne field compared to the current model results.

Furthermore this model gives a representation of the effect of a single push-convoy travelling along the groyne field to establish if groyne field nourishment can work as small feeder nourishments. For this ship type, about the largest and angulated ship type present on the Waal, the feeder nourishment works. When other ship types are applied in the model the behaviour of the groyne field nourishment could be different.

In this research the volume of the nourishment is kept constant while this probably has a significant effect on the effectiveness of the groyne field nourishment. When for example the nourishment is larger (in width, length or height) the capacity of the suction current may be fully used and more sediment is transported outside the groyne field. Also the front wave travelling into the groyne field has more effect stirring up sediment such that it is already suspended.

Furthermore bed update (morphology) was not simulated in XBeach and the initial nourishment is constructed in the model. The model gives therefore only the first reaction of the nourishment to the hydrodynamics by calculating the sediment transport rates, but not how the shape of the nourishment changes over time. The initial erosion of the nourishment presented in the current model results might get less real quick: when the parts of the nourishment that are exposed to suction are eroded first, the water gets more room to flow through and the friction gets less along the nourishment. This cause less sediment entrainment and less sediment transport.

In terms of the nourishment shape, from the model results is can be seen that the nourishments located up- or downstream were to much of a blockage for suction to be able to induce erosion at the left edge of the nourishment, but also for the river discharge to retain the current velocity to transport suspended sediment to the main channel. Lowering the height of the nourishment and detaching the nourishment from the groyne could help.

7. Conclusion

The question to be answered in this research was “how can groyne field nourishments act as small feeder nourishments that release sediment slowly to the main channel?” To answer this question at first a literature study was done to deepen the understanding of the hydrodynamics and morphodynamics in groyne fields without nourishment.

It appeared that navigation and river discharge are important components for the hydrodynamics and morphodynamics in a groyne field. The effect of navigation on the morphology is dominant over the effect of the river discharge when the groynes are emerged. Especially suction causes strong currents that mobilise and transport sediment out of the groyne field. The river discharge imports sediment from the main channel to the groyne field, but this transport is relatively small compared to the sediment export by navigation. Furthermore the circulation of the eddy may transport already suspended sediment, for example by secondary waves, to the main channel.

When the flow conditions increase (higher water level and river discharge) and the groynes get submerged, the effect of navigation gets rapidly less and the groyne field bottom is hardly effected by navigation. So the net sediment transport is into the groyne field by large-scale eddies and unidirectional flow over the groynes.

Groyne field nourishments will therefore only work as small “sand engine” in case of emerged groynes. This is the case for about 200 days per year. This finding leads to a limitation of the use of groyne field nourishments as measure against bed degradation.

The next step in this research was to get an initial understanding of the hydrodynamics and morphodynamics effecting the placed nourishment. Because very limited research is done before on groyne field nourishments, coastal and river processes were looked at to get knowledge of the possible behaviour of a nourishment.

It appeared that dune erosion and river bank erosion by waves and currents can be used to explain how nourishments erode. In the Waal these waves and currents are primarily induced by navigation. The ship waves, front wave, stern wave and secondary waves, attack the nourishment and suspend sediment. The suction current, cause by the water level depression when a ship passes, induces strong currents around the nourishment. These two components induced by navigation cause that the nourished material will break loose (avalanching) and fall along the nourishment; the nourishment gets lower and wider. When the front wave travels into the groyne field and when the nourishment stays below the water surface a negative feedback process is expected as it works along the same principles as for shoals along the coast.

Thirdly, the effect of the location in the groyne field and the shape of the nourishment on the way a nourishment act as small feeder nourishments was researched. By setting up a XBeach model for emerged groynes, three types of nourishments could be simulated. The nourishments had the same volume, but different locations and shapes: 1) one upstream in the groyne field, a sloped bump attached to the groyne; 2) One downstream in the groyne field, a sloped bump attached to the groyne; 3) And one in the middle of the groyne field, a peaked bump that rises above the water surface.

For all three nourishment the net sediment transport is directed to the main channel mainly induced by suction due to navigation. The other three important components are the front wave that causes suspension of nourished sediment and transport of the sediment to the river bank, and the stern wave and secondary waves that induces sediment entrainment at the nourishment edges. Furthermore, the nourishments do not lead to an increase of the flow velocities of the large-scale eddies due to the river discharge in the groyne field. This means that the nourishments do not induce (extra) erosion by large-scale eddies.

Navigation is the driving factor for eroding the nourishment. The erosion process of the nourishment is therefore dependent on navigation intensity on the river. Other important aspects are, among others, the dimensions of the ships and the distance to the groyne field.

Although all three nourishments can supply sediment to the main channel, it appeared that the downstream and the centre nourishment are the more effective nourishments. The downstream nourishment causes locally at the left and upstream edge of the nourishment high sediment transport rates. The centre nourishment causes high sediment transport rates, but less than for the downstream nourishment at the left up- and downstream edges of the nourishment. High sediment transport rates were also found in the rest of the groyne field, especially up- and downstream of the nourishment. Therefore the centre nourishment can cause erosion of the original groyne field bottom.

Furthermore the centre nourishment causes the primary eddy to be cut up into two eddies, one downstream and one up-stream of the nourishment. The circulation path of the eddy gets smaller and therefore the path to the main channel for suspended sediment is shorter. The flow velocity in the circulation did not decrease due to this separation. This effect of the centre nourishment is beneficial if secondary waves bring sediment in suspension after the ship has passed the groyne field.

Based on the above observations it can be concluded that the location of the centre nourishment is the most effective. Along all edges of this nourishment waves and currents induced by navigation attack the nourishment, the centre nourishment causes at the most places in the groyne field an increase of sediment transport to the main channel and the flow pattern in the groyne field is changed favourably for the sediment transport of already suspended sediment to the main channel.

The nourishments are tested for a groyne field at a straight part of the river where a loaded ship is sailing downstream. Further it can be said that when a ship is sailing upstream the effect of navigation in the groyne field is stronger, this is also the case when multiple ships are sailing in file or overtake each other along the groyne field.

So in the end it is determined that groyne field nourishment can work as small feeder nourishments that release sediment slowly to the main channel in the case of emerged groynes for about 200 days per year.

8. Recommendations

In this chapter recommendations are made how the model research can be used and what aspects need further study.

Nourishment material

For this research the material of the nourishment was not included in the scope, but it is a significant factor in the working of groyne field nourishments. When the material is too coarse the nourishment may change the dynamic equilibrium in the groyne field, but when the material is too small it has the opposite effect in the main channel: bed degradation is enhanced. Therefore a close look is needed on the nourishment material.

Field research

Unfortunately no recent data is available of the hydrodynamics and morphodynamics in a groyne field along the Waal and therefore it is advised to do field measurements to get a better understanding of these dynamics. A clear and concise documentation of measurement specifications (location measurements points, ship types, distance from river bank to ship etc) will contribute to a deeper and better understanding of the effects of different nourishment options. This will in the end help with assessing the effectiveness and efficiency of groyne field nourishments compared to other measurements against bed degradation in river.

XBeach

In further research the question is whether you should use again XBeach. In the end XBeach is made for coastal processes on short time scale for small spatial scales. XBeach can simulate the primary waves, but the simulation of secondary waves during low flow conditions is unclear. Besides XBeach has trouble with simulating river discharge on a smaller scale. When for example the effect of a groyne field nourishment for a longer period with multiple flow conditions needs to be simulated Delft3D might be a better choice. Delft3D can simulate river discharge in a stable way for a smaller grid and can simulate primary waves. The secondary waves will not be simulated is this case, but according to the literature the contribution of the secondary waves to the suspension of sediment is much less than suction. An option for a smaller grid and a larger simulation time provides the opportunity to also simulate the morphology.

Further the option to couple a XBeach model for the the effect of navigation with a Delft3D model for the effect river discharge is worthwhile to discover. Probably this provides the option to have the best of both worlds: detailed ship wave simulation with XBeach and a stable river discharge simulation for a longer period and for a larger area.

This more extensive model probably can give an insight in the question what happens with a groyne field nourishment during high river discharge (flood flow conditions). Also, will a nourishment supply sediment to the main channel when it is for example placed at a location where water flows from the floodplain to the main channel?

Expansion model

When a suitable simulation model is available (e.g. XBeach in combination with Delft3D) further research needs to be done to assess the effects of:

- Loaded/unloaded ships
- Ships sailing up- or downstream
- Different type of ships
- Multiple ships behind each other
- Ship manoeuvres, for example overtaking
- Bends (outer, inner bend) and straight parts of the river
- Nourishment volume
- Nourishment material
- Series of groyne field nourishments
- Applying nourishment on both sides of the river

In addition, simulating a groyne field nourishment over a longer period, for example a year, would provide new insights about the behaviour of the nourishment during all flow conditions and the effects of transitioning from emerged to submerged groynes.

The next question that might be asked is: will the nourishment fully erode in the low water season of the river or is the period of low flow conditions too short? And do the nourishment supply enough sediment to the main channel to compensate for the shortage of sediment in this situation? A series of nourishment in subsequent groynes at both river bank of the Waal maybe an option to obtain enough supply capacity to avoid further large-scale bed degradation in the main channel of the river.

Each aspect that is researched ensures a better understanding and prediction of groyne field nourishments and the effectiveness of small feeder nourishment for river erosion reduction.

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A. Waal

A.1 History of the Waal

In the following the history of the Waal is elaborated to explain the occurrence of the current problem: bed degradation.

The Waal has a rich history of river regulation measures and most of these measures were taken to improve the living conditions along the Waal.

The first river regulation measures were done between 1150 and 1350 and were focused on the construction of local dikes to protect for floods. Between 1595 and 1680 groynes and longitudinal dikes along the main channel were built to prevent erosion of the riverbanks and to catch sediment to create farmland in the floodplain (Ten Brinke, 2004).

Later, between 1639 and 1655, measures were taken to prevent dike breaches due to ice jams in the winter. These ice jams used to occur in the shallow areas of the Waal where flow converges. By closing of secondary channels, cutting off river bends and placing groynes, the flow velocities in the Waal were increased and the formation of sandbanks was prevented. Another effect of the measures was that the main channel of the river was deepened by erosion, which was beneficial for navigation (Smedes et al., 2006).

A groyne keeps, for example, the high flow velocities in a river away from the river bank, such that the river bank is not attacked by the strong water current. This strong current can induce destabilisation of of the river bank by eroding sediment from the river bank. Therefore, by constructing groynes the bank protection is established. Groynes also induce deepening of the main channel. The cross-sectional area of the river is limited, because the groynes are blocking the flow near the river banks. As a consequence the flow velocity increases in the centre of the river and with that also the bed shear stress increases over there. This causes an increase of erosion of the bottom material, which results in deepening of the main channel.

The series of groynes form together a long constriction in the Waal which cause an increase of the water depth and a reduction of the bed slope (the relative increase in the water depth is larger than the relative reduction of the slope) (De Vriend et al., 2011). By adjusting the length of the groynes the equilibrium bed level in the river can be changed locally (Uijttewaal, 2007).

Since 1655 to 1817 more groynes were constructed along the Waal. The groynes were placed at regular intervals to direct water flows away from the riverbanks. Therefore the riverbanks were saved from erosion and the width of the main channel was normalised and narrowed. In figure A.1 the top panel shows the Waal in 1817 after amongst other measures the above described measures.

The next river regulations measures were two large scale width normalisations, the first one between 1850 and 1888 (middle panel in figure A.1 and the second one between 1888 and 1890 (bottom panel in figure A.1 (Ten Brinke, 2004).

After the second normalisation the main channel of the Waal became about 150 m wide and 2.5 m deep during agreed low water level. The agreed low water level in a river forms a reference plane to which depths are indicated for shipping. Dredging works were done when the river did not meet conditions anymore (Smedes et al., 2006).

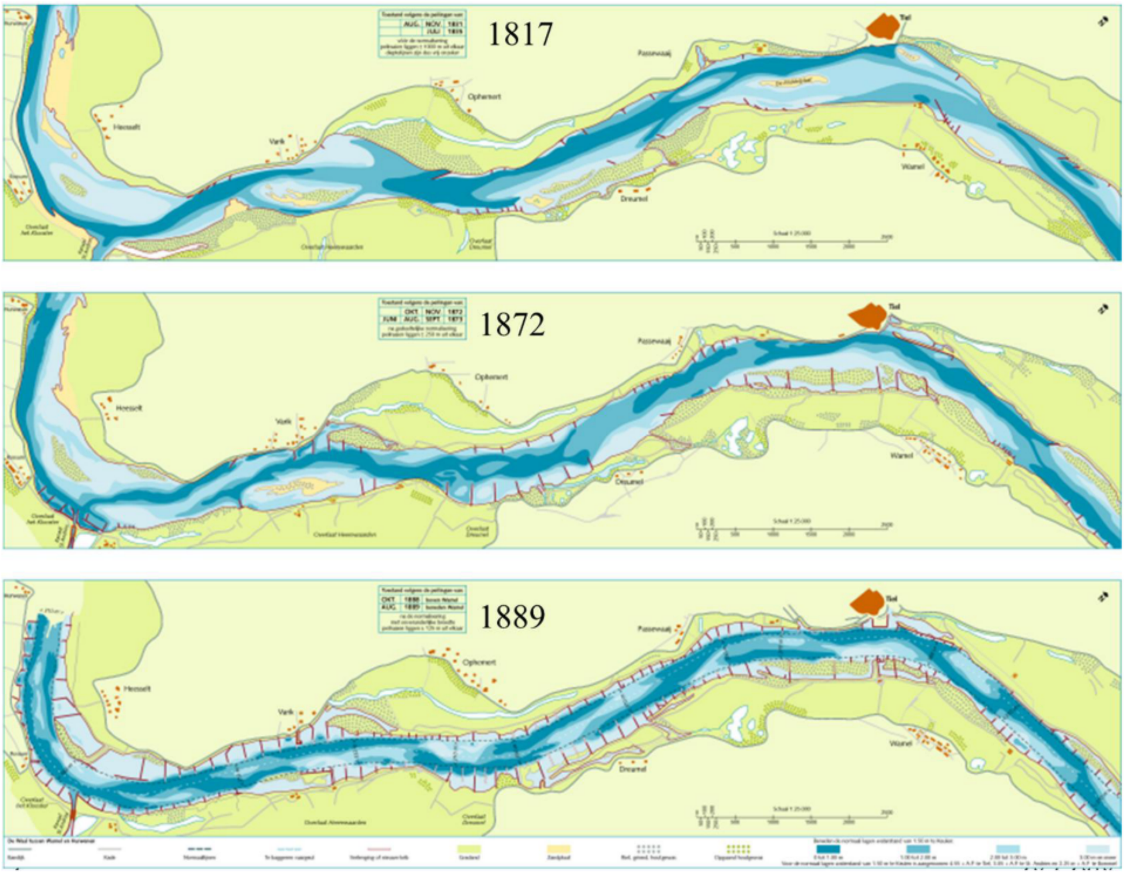


Figure A.1: Normalisation of Waal River (Havinga, 2016)

After these two normalisations it appeared that the cut-offs lowered the upstream parts of the river in Germany. When the lowering continues more water will flow into the Waal at the bifurcation of the Rhine into the Waal and the Pannerdensch Kanaal. To keep the Pannerdensch Kanaal available for navigation, no cut-offs would be done in the future and other river bend improving measures should be looked at (Smedes et al., 2006).

At the end of the 20th century there was a plan to allow bigger ships (6-barge push-tows) on the Waal. The Netherlands and Germany set up a program to achieve this: the Waal Project. The objectives of the Waal Project were (Smedes et al., 2006):

- Increase main channel dimensions to 170 m x 2.80 m at OLR (agreed low water level);
- Stop bed degradation, because the riverbed degraded with several cm per year;
- Obtain surplus values for the river's ecosystem by integrating floodplain rehabilitation plans.

For the project, at the bend of the Waal near Nijmegen, a fixed layer (constructed in 1986) as permanent measure and dredging works as recurrent measure were taken. In appendix A.2 the effect of the fixed layer in the Waal is explained in detail.

Due to the fixed layer the width the main channel in the bend near Nijmegen increased with about 50 m with an available depth of 2.50 m at Q5% (low water).

Due to the permanent bend improvement, the fixed layer, the main channel of the Waal is about 150 m wide and the bottom level varies between -2.50 and -1.10 m below NAP (Normal Amsterdam Level).

The next river regulating measures were done from the summer of 2009 until the end of 2015. About 460 groynes along the Waal, between Nijmegen and Gorinchem, were lowered by an average of 1 m. Due to the lowering of the groynes the water level in the Waal during high water (about 11,000 m^3/s) decreases with 6 to 12 cm (Rijkswaterstaat, 2013). Furthermore, longitudinal dams are constructed in the Waal over an area of 10 km that may change the helical flow (explained in appendix A.2) such that less sedimentation occurs and less dredging works are needed. The groynes at the location of the longitudinal dams have been removed.

Nowadays a major concern is the fixed layer at Nijmegen since it creates a hard point in the river which with continuing degradation will be increasingly a bottleneck: a very shallow point in the river. Navigation will not be able to pass Nijmegen during low water conditions and therefore the loading capacity decreases. Furthermore due to the abrupt change in water depth, ships touch the fixed layer, which can damage the ships.

Until now the negative effects of the fixed layer, especially the deposition region in the inner bend downstream of the fixed layer are compensated by dredging works. However, measures will be taken in the short term: the surface of the hard layer will be flattened by removing bumps. Furthermore a gradual transition from the fixed layer to the sandy river bottom will be constructed. This will make the transition from deep to shallow waterways less abrupt, so that the inland vessels are less likely to make contact with the hard layer and be damaged.

But when the large scale bed degradation in the Waal and the Upper Rhine will not stop the fixed layer again will be a bottleneck for navigation within a couple of years. So a durable solution against bed degradation would be more ideal.

A.2 Fixed layer

To be able to explain the effect of the fixed layer, first the water flow in a river bend without fixed layer is discussed. In figure A.2 this water flow is schematised.

The water that flows through the river experiences friction at the river bed and river banks. The flow velocity is the highest at the water surface, somewhere in the middle of the river. In a river bend the water flow follows a curved streamline and therefore experiences a centrifugal apparent force. The water mass is pushed out to the outer bend and the water surface level raises at this point. Globally the centrifugal apparent force is compensated by a pressure force directed towards the inner bend. Locally this is not the case, because the centrifugal apparent force and the pressure force are differently distributed over the water mass. This is because the centrifugal apparent force depends on the flow velocity and varies at every location. Near the water surface the flow velocity is relatively high, so the net force is directed towards the outer bend. Close to the bottom, where the flow velocity is relatively low, the net force is directed towards the inner bend. The results of these forces is that the water flows near the water surface to the outer bend and near the bottom the water flows to the inner bend, this combined with the main flow forms the helical flow (Ten Brinke, 2004).

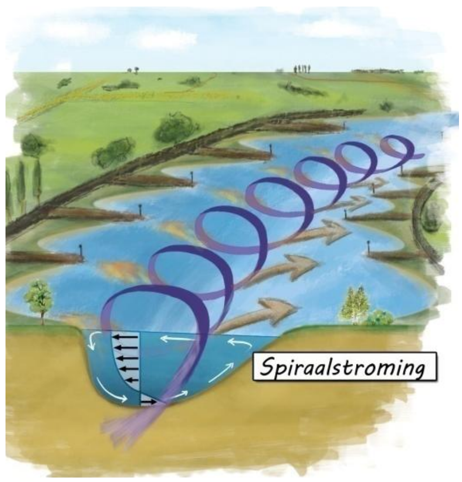


Figure A.2: Helical flow (Schuurman, 2012)

The helical flow has an impact on the sediment transport through the river bend. The sediment transport along the bottom is directed towards the inner bend, therefore sedimentation occurs in the inner bend. At the outer bend a net loss of sediment occurs, which results in erosion at the outer river bank and river bed. Due to the combined effects of sedimentation and erosion the bed of the river in the cross-section slopes (Ten Brinke, 2004).

This process continues until the gravity compensates the cross-sectional sediment transport. Furthermore the water flow in the outer bend experiences less friction, due to the increased depth, so the water flow will be concentrated in the outer bend. The outer river bank is attacked by the water flow and the inner bend stays protected. When the river has no fixed river banks, this results in a diversion of the river (Ten Brinke, 2004).

On the left in figure A.3 a river bend with a fixed layer in the outer bend is shown and on the right side the morphological effect of the fixed layer can be seen. A fixed layer consists of sand and gravel protected by a layer of riprap. Due to the fixed layer the cross-section of the river gets another shape with uniform depth, therefore more discharge will flow through the inner bend and therefore more sediment is transported along the inner bend. The water flow in the outer bend gets clear of sediment. These effects are enhanced by the increased hydraulic roughness of the outer bend by the surface of the riprap. The total effect of the fixed layer is that the flow strength increases in the inner bend and less sedimentation occurs. The depth of the inner bend increases (Ten Brinke, 2004).

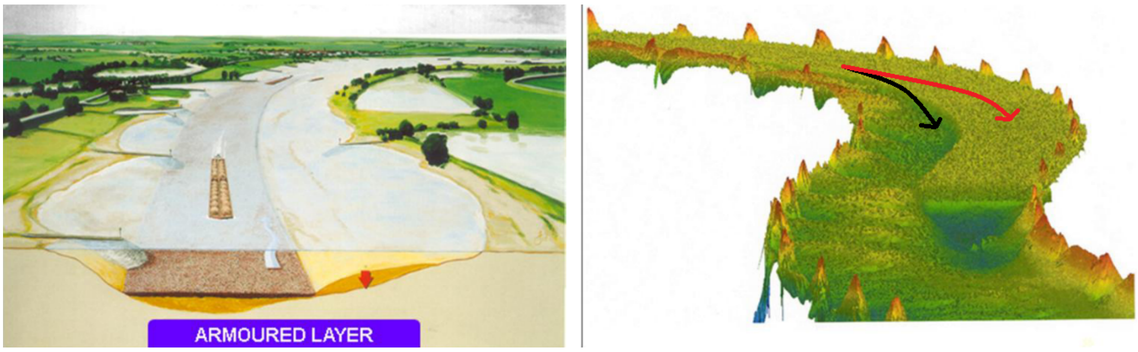


Figure A.3: Fixed layer, red arrow: water flow before construction of fixed layer, black arrow: water flow after construction of fixed layer (Havinga, 2016)

Downstream of the fixed layer the original, natural cross-section of the river appears again. So downstream, in the inner bend, a permanent shoal develops, because more sediment is transported through the inner bend in case of a fixed layer than for the natural cross-section. Downstream in the outer bend erosion occurs due to a shortage of sediment. In figure A.3 on the right the erosion pit (dark green) and the shoal (yellow) are shown downstream of the fixed layer (Havinga, 2016).

In the bend near Nijmegen the increase of the main channel width amounts to about 50 m with an available depth of 2.50 m at Q5% (low water). About 80% of the cross-sectional changes took place within 2 years (Smedes et al., 2006).

B. Flow hydrodynamics

In this appendix flow loads (wall flow, free flow and turbulence) and flow separation are elaborated.

B.1 Flow loads

When a fluid moves along a wall, wall flow, a boundary layer develops. A boundary layer is the region in the flow that is affected by the presence of for example a river bank. In a river the flow is non-linear, the accelerations and decelerations of the flow influence the boundary layer and therefore also influence the turbulence in the flow according table B.1.

Table B.1: Wall flow (Schiereck & Verhagen, 2016)

	Cause	**Effect on boundary layer**	**Effect on relative turbulence**
Accelerating flow	Pressure gradient in the flow direction	Decrease	Decrease
Decelerating flow	Pressure gradient in the opposite flow direction	Increase	Increase

When two bodies of fluid move along each other with different velocities, it is called free flow. A mixing layer grows between the two fluids. The fluid body with the smallest velocity accelerates and the fluid body with the largest velocity loses momentum and decelerates. Between the two fluid bodies the shear stress is high which induces turbulence (Schiereck & Verhagen, 2016).

Flow along groynes consist of a combination of wall flow and free flow, so boundary layers and mixing layers are present. Flow separation is the transition between wall flow and free flow. In figure B.1 flow separation around a groyne is shown. From B the velocity decreases and the boundary layer increases until point D. From point D flow separation occurs. Flow separation increases turbulence (Schiereck & Verhagen, 2016).

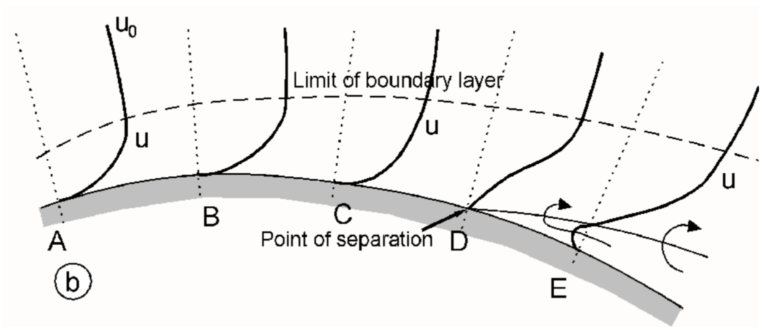


Figure B.1: Flow separation around round body (Schiereck & Verhagen, 2016)

Turbulence is caused by a velocity gradient perpendicular to the main flow direction. The velocity difference is too large for the molecular viscosity to prevent formation of turbulent eddies. The velocity and pressure in a turbulent motion are fluctuating irregularly. When turbulence exist between a wall and flow it is called wall turbulence and when turbulence exist between two flow zones it is called free turbulence. River flow is always turbulent (Schiereck & Verhagen, 2016).

B.2 Flow separation

As earlier stated: river groynes cause flow separation. When the groynes are emerged the flow is streaming around the groyne and not over the groyne. When the groynes are submerged the flow is streaming over the groyne. In the following flow separation is elaborated further.

Submerged groynes cause a sudden decrease followed by a sudden increase in depth, so flow separation occurs in the vertical plane. In figure B.2 this flow situation is shown. Emerged groynes cause a sudden horizontal constriction followed by a sudden expansion so flow separation occurs in the horizontal plane. In figure B.3 this flow situation is shown.

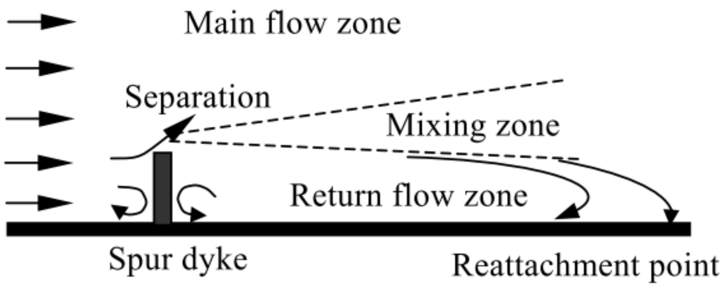


Figure B.2: Flow zones (Zhang & Nakagawa, 2008)

Looking at a single groyne, the separation region downstream of the groyne in a rectangular channel can be subdivided into four zones. The locations of these zones are illustrated in figure B.2. In the figure the flow around a spur dyke is schematised, but the zone locations are the same for groynes.

In the main flow zone the water flow is accelerating, because the channel width/depth is reduced. In the return flow zone or the recirculation zone two eddies appear each different in size and they rotate in different directions. The smaller eddy is located near the groyne and the larger eddy is located downstream of the small eddy (Zhang & Nakagawa, 2008).

The velocity difference between the main flow zone and the return flow zone leads to a shear layer; the zone around this layer is called the mixing zone. The mixing zone starts at the tip/top of the groyne and grows in width/depth downstream. An important aspect of the mixing zone is the vortex due to periodic water level fluctuations by migrating vortices. The velocity of these vortices is a bit larger than the velocity of main water flow. The vortices merge and migrate downstream.

Next to this migrating vortices also horse-shoe vortices and a wake vortex system are formed. At the upstream side of the groyne the flow stagnated, therefore a bow wave near the water surface and a down flow towards the channel bed arise. This flow separations induces a horse-shoe vortex in the local scour hole upstream of the groyne and a wake vortex system downstream of the groyne (Zhang & Nakagawa, 2008).

The reattachment point is the point where the boundary streamline attaches the river bank/bottom again. This point is moving back and forth in a certain area: the reattachment zone. This point is constantly moving because of unstable eddies in the shear layer and because of the pressure gradient between the main flow and recirculation zone: near the reattachment point the pressure is high and in the recirculation zone the pressure is low due to the entrainment of water in the main flow. The pressure difference induces flow from the reattachment point in the opposite direction of the main stream. From the reattachment point a new boundary layer grows (Yossef, 2002) .

The return flow zone and the reattachment zone together is called the wake.

For horizontal flow separation the mixing layer is curved, because the flow is forced to the centre of the channel by the main flow. Horizontal flow separation can be seen in figure B.3. In the mixing layer the turbulence intensity is high. The accelerating flow (arrows) causes a decrease in relative turbulence and in the deceleration zone (stagnant) the relative turbulence increases (Schiereck & Verhagen, 2016).

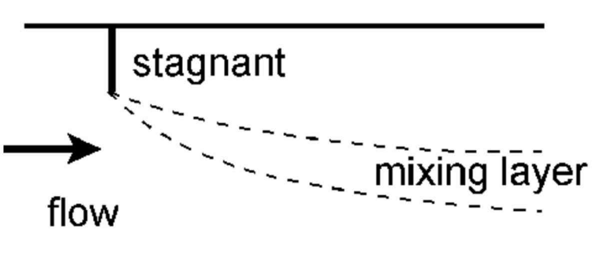


Figure B.3: Horizontal constriction and expansion (Schiereck & Verhagen, 2016)

C. Flow morphodynamics

In this appendix flow stability, sediment transport and sediment properties are elaborated.

C.1 Flow stability

This section elaborates on the behaviour of grains, which are exposed to currents. According the Shields approach grains will start moving when the friction force exceeds a certain critical value, the bed erodes. The friction force is caused by water streaming along the bed. Shields approach is valid for permanent uniform flow, but can be adapted for non-uniform flow and for a sloping beds by implementing correction factors in the Shields relation. These factors are already defined for groynes.

The grain dimensions of sediment is an important factor in the behaviour of sediment. A lot of ambiguity is present in defining sediment material, because of different shapes and the different sizes of the grains.

Flow erosion occurs around groynes: local scour. Scour occurs when the local sediment transport exceeds the sediment supply from upstream. The difference between the import and export of sediment can be caused by a difference in velocity, turbulence or both.

Groynes causes accelerations and decelerations and therefore induce turbulence. Due to turbulence the sediment is brought in suspension, this leads to an increase of the sediment transport and this causes scour. The scour stops when the amount of supplied sediment from upstream equals the amount of eroded sediment. The eroded sediment settles further downstream.

The scour hole induces flow separation. Therefore a mixing layer and a recirculation zone are occurring in the scour hole. In this way the scour hole causes scour itself. When the velocity in the scour hole decreases, so no sediment is picked up by the circulating flow, the scouring process stops and the final scour depth is reached.

C.2 Sediment transport

Sediment transport is the movement of sediment particles through a well-defined plane over a certain period of time. The sediment particle movement depends on the properties of the transported material (grain size, fall velocity). These properties are elaborated in detail in appendix C.3. A sediment grain starts to move when the water above exerts a large enough shear stress on the grain, this amount of shear stress describes the initiation of motion.

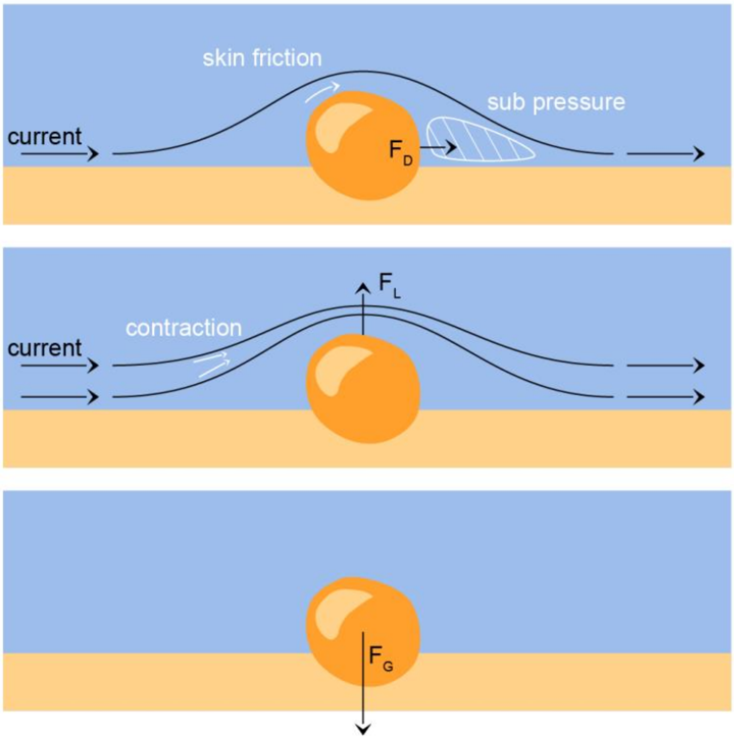


Figure C.1: Forces on an individual grain in a stationary situation (Bosboom & Stive, 2015)

In figure C.1 the forces on an individual grain in a stationary situation are shown. The drag force is a combination of skin friction acting on the grain surface and the pressure difference between the up and downstream sides of the grain due to flow separation. The lift force results also from the flow separation and from the flow contraction above the grain: a higher flow velocity results in a lower local pressure (Bernoulli law). The difference in pressure causes an upward directed lift force. The gravity force results from the gravity of the earth.

Gradation of the bed material plays a role in sediment transport. In case of well-graded sediment the smaller particles will be hidden in the voids between the larger particles and the larger particles will be more exposed. At the top layer of the bed the smaller particles will be washed out, the coarser top layer prevents the movement of underlying smaller particles. This is called armouring.

Furthermore a sloping bed in the flow direction will increase of decrease the critical flow velocity. The cohesive forces also influence this critical flow velocity, for cohesive sediment the resistance against erosion is increased.

There are two transport modes:

- Bed load: sediment particles roll, shift or make small jumps (saltations) close to the bed, the particles are in more or less continuous contact with the bed. During high shear stresses an entire layer of sediment is moving, this is called sheet flow. Bed load transport responds instantaneously to the bed shear stresses.
- Suspended load: grains are lifted from the bed at flows above the critical flow velocity and transported in suspension by moving water. There is no contact between the grains and the bed. The particles are kept in suspension by turbulent diffusive forces.

In figure C.2 the different modes of sediment transport are shown and in figure C.3 the location of the suspended and bed load are given.

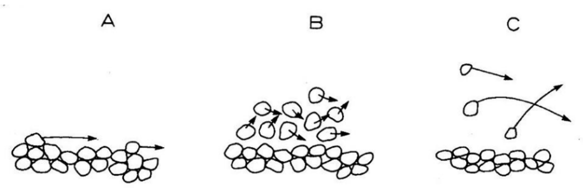


Figure C.2: A: Bed load, B: Sheet flow, C: Suspended load (Bosboom & Stive, 2015)

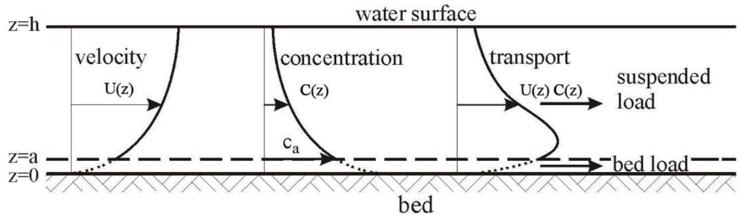


Figure C.3: Location of the suspended and bed load (Bosboom & Stive, 2015)

C.3 Sediment properties

There are cohesive and non-cohesive materials. Clay is for example cohesive, which means that the grains stick together because the surface area of the grain gets chemically active especially when the clay is wet. Sand is for example a non-cohesive material, the grains do not stick together.

In addition to the cohesiveness of a material the following properties of the sediment material (grains or in bulk) are important for sediment transport:

- Grain size (median particle diameter and the grading)
- Grain density
- Relative density (ratio of the grain density over the water density)
- Fall velocity (depend on the grain characteristics and the fluid characteristics)
- Angle of repose
- Porosity (ratio of the pore space to the whole sediment volume)
- Sediment concentration (mass concentration: mass of the solid particles per volume, and volume concentration: ratio of the volume of solid particles to the whole volume)

The fall velocity is defined as when a particle fall in still and clear water, it accelerates until it reaches a constant vertical velocity, the fall velocity. The drag force directed upward and the gravity force directed downward influence the fall velocity.

In high concentration mixture the fall velocity of a single particle is reduced due to the presence of other particles: when a grain moves downward, a similar fluid volume must flow upward, this upward flow slows down the grain movement.

D. River discharge

In this appendix the hydrodynamics and the morphodynamics related to the river discharge are further explained.

D.1 Types of flow patterns in a groyne field

The flow pattern in the groyne field, between emerged groynes, is influenced by the bottom slope, geometry, the location in the river (inner bend, outer bend or straight part) and the groyne orientation.

Six types of flow pattern in groyne field can be distinguished and are illustrated in figure D.1:

1. The main flow is deflected outside the groyne field and one primary eddy appears, what prevent the main flow to penetrate into the groyne field.
2. The main flow is deflected outside the groyne field and two equal eddies appear, what prevent the main flow to penetrate into the groyne field.
3. The distance between the groynes increases. Now the water flows into the groyne field and a strong eddy near the upstream groyne develops. Furthermore at the downstream groyne a lot of turbulence appears.
4. There is no stable eddy present in the groyne field, a strong reverse current occurs.
5. The water flows to the river bank after being diverted by the upstream groyne. The two eddies next to the flow protect the river bank.
6. The distance between the groynes increases. The downstream eddy disappears and the flow causes erosion of the river bank.

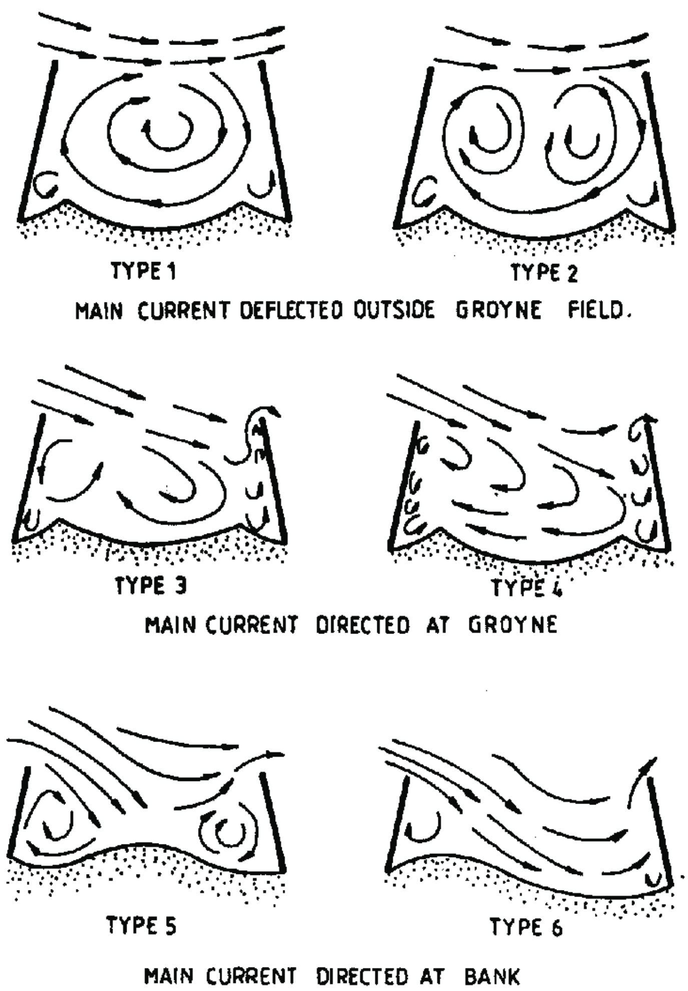


Figure D.1: Flow pattern in groyne field (Yossef, 2002)

Number 1 and number 2 flow patterns are beneficial for navigation, since the main flow is deflected outside the groyne field and a deep channel is maintained (Yossef, 2002).

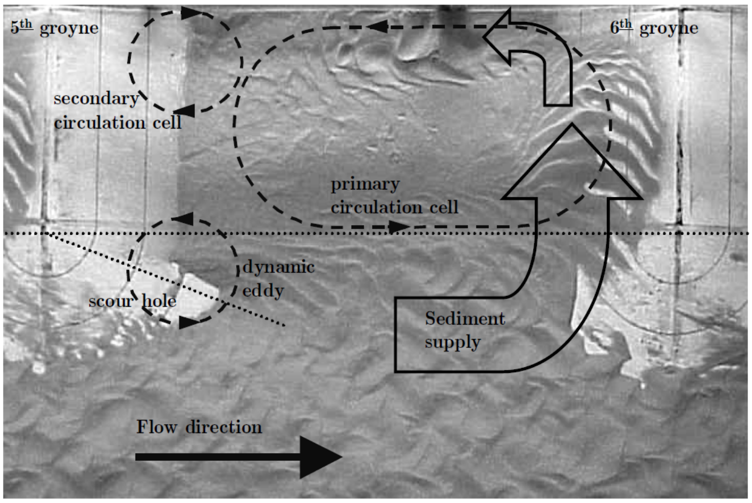
D.2 Morphodynamics - small scale

In this appendix the morphodynamics on a small scale will be discussed. At a small scale the effects of the different hydrodynamic forcings on the behaviour of one groyne field can be determined for a relatively short period of time. In figure D.2 the morphological pattern in a groyne field for emerged groynes and for submerged groynes are shown. Each morphological pattern consists of a couple of characterising structures.

In case of emerged groynes ripples can be seen near the river bank. Those are developed in the opposite direction of the main flow and in the direction of the primary eddy. The ripples indicate that the primary eddy flows close to the river bank. In the centre of the primary and the secondary eddy no bed forms appear.

In case of submerged groynes the main flow is not directed towards the groyne field. Still a significant sediment transport from the main channel to the groyne fields is present.

In case of the emerged groynes, the sediment is mainly advected towards the groyne fields by the primary eddy. In the case of submerged groynes, the sediment is transported to the groyne fields across the normal line of the groyne, primarily by residual advective transport by large-scale coherent structures, but also by diffusion by the unidirectional flow.



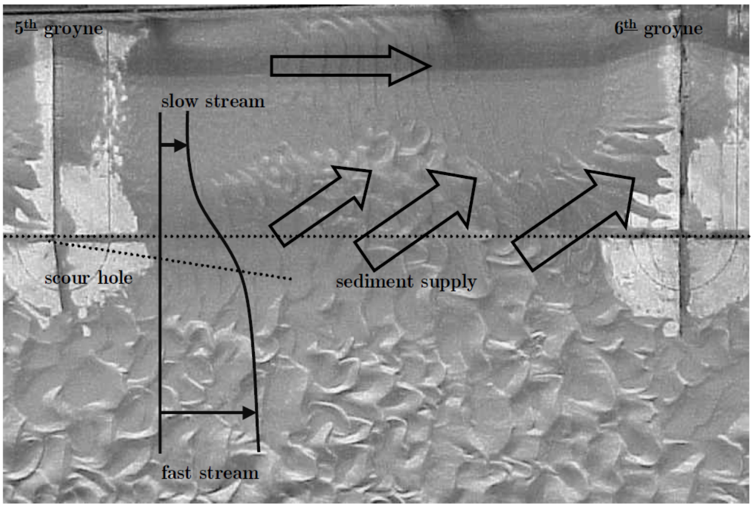


Figure D.2: Morphological pattern for emerged (top) and submerged (bottom) groynes (Yossef, 2005)

The submergence ratio influences the magnitude of the morphological structures. With increasing submergence the characteristics of the mixing layer change, such that the turbulent intensity as well as the velocity gradient across the mixing layer decrease. This weakens the large scale coherent flow structures and therefore the sediment exchange between the main channel and the groyne fields decreases.

At a certain point the submergence ratio gets to a level that the velocity gradient in the mixing layer gets too weak to induce large-scale coherent structures.

The location of the deposition region shifts towards the river bank when the submergence ratio increases.

The alignment of the scour holes also responds to the submergence ratio. For small submergence, the scour hole intrudes into the main channel and for large submergence the scour hole is directed to the flow direction and is fully impounded inside the groyne fields. Also both alignments can appear, so two scour holes in a different direction. This happens when the groynes become emerged and submerged depending on the river flow conditions. For those two conditions the path of the dynamic eddy is different, which contributes to the different alignments.

The maximum scour depth also responds to the submergence ratio. When the submergence ratio increases the maximum scour depth decreases, because the turbulence intensity gets less. When the submergence ratio gets too large the effects of a groyne disappears.

The height of the groynes has no effect on the sediment exchange between the main channel and the groyne fields.

E. Wave hydrodynamics

In this appendix wave parameters and characteristics, wave direction, wave shape, wave breaking, dynamic pressure, wave-induced set-up and wave-induced currents are elaborated.

E.1 Wave parameters and characteristics

Waves are oscillations of the water surface generated by ships. In figure E.1 a simple representation of a wave is given. The parameters of a wave are: the wave height (H), the wave length (L), the amplitude (a), the surface elevation (η), the period (T) and the wave speed (c). The steepness of the wave is defined by the H/L ratio.

A wave is characterised by the height, period and the propagation direction. The wave characteristics together with their duration are dependent on the characteristics of the wave field (speed, duration, direction) and local water depth.

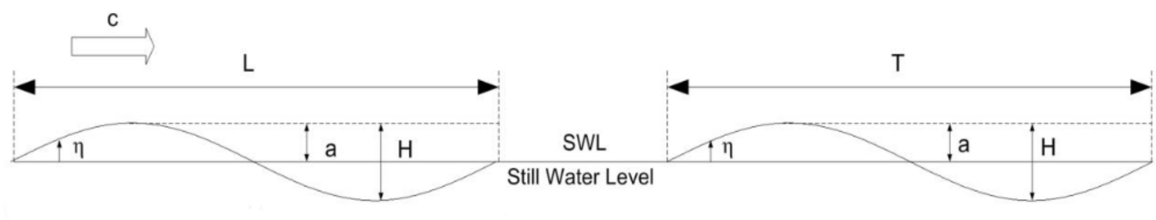


Figure E.1: Left: spatial variation of a wave, right: temporal variation of a wave (Bosboom & Stive, 2015)

E.2 Wave direction

During normal and low water conditions in the river, the groyne field beaches fall dry and get visible, figure E.2 shows a groyne field beach. When a ship wave approaches this beach at an angle, defined as oblique incident waves, water depth and therefore also the phase velocity changes occur along the wave crest. The wave crest in the deeper parts travels faster than the wave crest in shallow parts. This forces the wave crest to bend towards shore normal (perpendicular to the depth contours). This process is called refraction. Therefore ship waves propagate into the groyne field along the normal line of the groyne field beach.

Figure E.2: Groyne field beach along the Waal appearing during low water conditions (Van Lokven, 2011)

Refraction can cause an increase or a decrease of wave height when the depth contours are not straight and parallel to the shore line: in figure E.3 a refracting wave ray, S, is shown. A wave ray represents the direction of propagation of the wave at any point along it. Wave rays are perpendicular to wave fronts. When wave rays converge, accumulation of energy occurs. This causes an increase of wave height. In the opposite way, when wave rays diverge a decrease of wave height is observed.

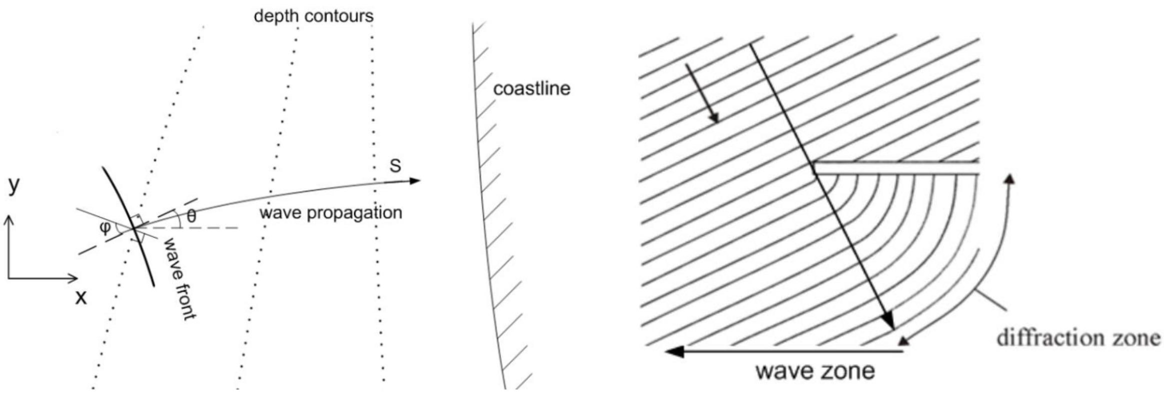


Figure E.3: Left: Definition of wave angles for a wave propagating along a wave ray S; Right: Diffraction (Bosboom & Stive, 2015)

In rivers current-refraction may occur. The short secondary waves interact with the river flow and the phase velocity of the wave will be affected. When the phase velocity differs along a wave crest, current-refraction occurs.

Next to refraction also diffraction could occur when ship waves approach a groyne field. Diffraction occurs when obstructions to the wave propagation or abrupt changes in the bottom contour are present, for example groynes. Wave energy is transferred along the wave crest out of the wave ray into the shadow zone (leeward of the obstacle). A wave ray give the propagation direction of a wave group as can be seen in the left panel of figure E.3. The wave height of the initial wave ray decreases. The extent of energy penetration behind a obstacle depends on the ratio of the characteristic lateral dimension of the obstacle. Diffraction of an incident wave train is schematises in the right panel of figure E.3.

E.3 Wave shape

During shoaling the wave crest is gradually peaking and the troughs are gradually flattening, this is called skewness. Furthermore, steepening of the wave face occurs until breaking, the wave gets a pitched-forward shape, this is called asymmetry. The wave shapes in case of skewness and asymmetry can be seen in figure E.4

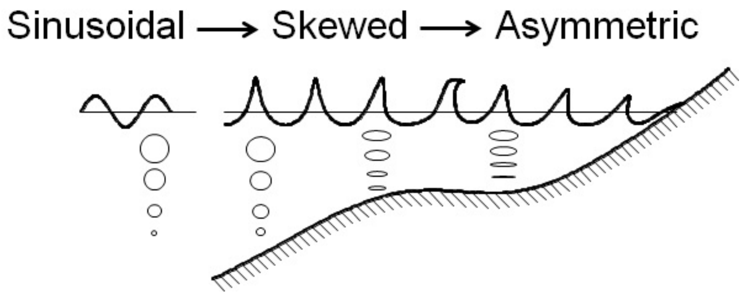


Figure E.4: Wave shape nearshore (Rocha, 2014)

E.4 Wave breaking

Shoaling of ship waves is limited by wave breaking. During shoaling a wave crest becomes unstable and will start breaking. Breaking happens when the particle velocity exceeds the phase velocity.

Depth-induced wave breaking

Underneath the water surface the fluid particles describe an orbital path. In figure E.4 these orbits are given for deep, intermediate and shallow water. In deep water the orbits are closed circles. These orbits becomes closed ellipsoids in water of finite depth and near the bottom the ellipsoids become flatter. At the bottom the vertical velocities are zero and the further from the water surface the smaller the orbit diameter becomes. In very shallow water, from the surface to the bottom, the vertical displacement of the water particles become zero and the horizontal displacement remains almost constant.

Shoaling results in a significant increase in horizontal particle velocities with respect to the phase velocity. This is because the phase velocity reduces, when the wave approaches the shore. In addition, shoaling causes an increase in the wave height. Because the vertical axis of the orbit at the water surface is equal to the wave height, the vertical motion of the water particles at the surface must also increase due to shoaling. The horizontal movements grow in relation to the vertical movements and a significant increase of the particle velocity near the surface is induced. At a certain moment the horizontal particle velocity exceeds the phase velocity and the wave breaks.

Steepness-induced breaking

For steepness-induced wave breaking two breaking criteria are set up for deep water and shallow water (only valid for a horizontal bottom). In deep water steepness-induced wave breaking is called white-capping. The breaking criterion in deep water is as follows:

$$\left[\frac{H_0}{L_0}\right]_{\max} \geq 0.142$$

In shallow water the breaker index γ can be used: wave breaking occurs when the wave height becomes greater than the water depth, in appendix E.4 this is explained in detail. Therefore breaking in shallow near-shore zone is called depth-induced wave breaking.

$$\gamma = \left[\frac{H}{h}\right]_{\max} \geq 0.88$$

Based on the ratio of the slope steepness, $\tan(\alpha)$, and the wave steepness, H_0/L_0, the Iribarren parameter, the breaker type can be defined:

$$\xi = \frac{tan(\alpha)}{\sqrt{H_0/L_0}}$$

In figure the different types of breaking can be seen for different values of the Iribarren parameter:

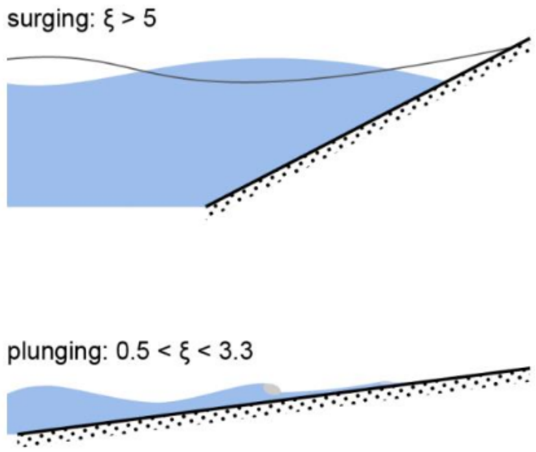


Figure E.5: Breaker types (Bosboom & Stive, 2015)

When a wave breaks a layer of air-water mixture which moves landward in the upper parts of the water column can be seen. This could be temporary storage of energy and momentum: wave energy is first converted into turbulent kinetic energy (roller at face of breaking wave) before it is dissipated by the production of turbulence.

Velocities in breaking waves

Propagating waves transport energy and momentum. Momentum is defined as the product of mass and velocity, so this can be seen as a mass flux: a water particle has a mass, and if the particle is moving it has momentum.

In the surf zone the mass flux is larger than outside the surf zone, this is because of:

- Progressive character of waves
- Surface roller in breaking waves

At a closed boundary (riverbank) there is a zero net mass transport in the vertical (otherwise the water will increasingly pile up against the boundary). Therefore a net velocity is needed below the water trough level to compensate for the mass flux above the water trough level: the return current. In non-breaking waves this return current is small. In breaking waves the return current is large, because the mass transport towards the boundary between the wave crest and the wave trough is also large. The return current in breaking waves is called undertow.

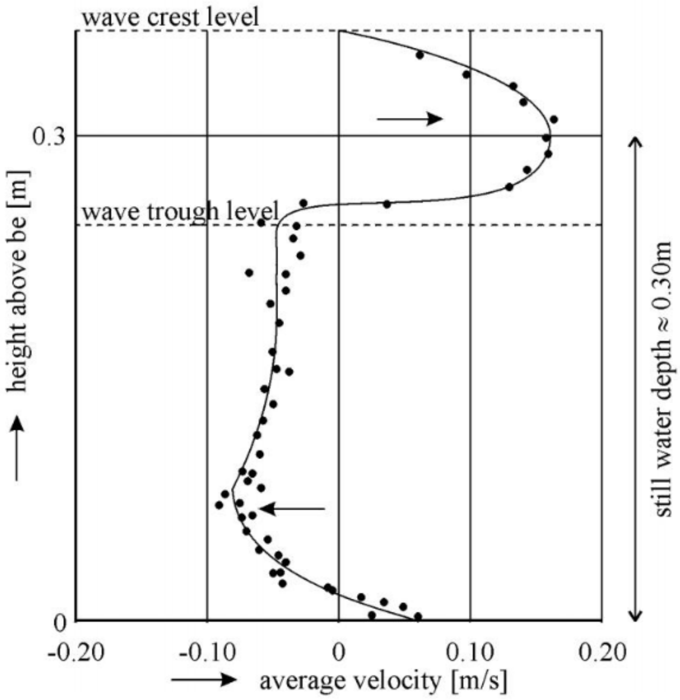


Figure E.6: Velocities in a breaking wave averaged over a wave cycle under propagating waves (Bosboom & Stive, 2015)

In figure E.6 the velocities in a breaking wave can be seen. Around the still water level, directed to the right, the mass transport of the breaking wave can be seen. In the middle part of the water column the return current (undertow), directed to the left, is indicated and close to the bed Longuet-Higgins streaming can be seen. This streaming is a non-zero wave-averaged horizontal flow.

Longuet-Higging streaming is caused by the wave boundary layer: water moving along the bed incurs a shear stress on the bed, which can set sediment grains into motion. The wave boundary layer dissipates energy form the flow above.

In the lower and middle part of the water column relatively high sediment concentrations are present due to wave breaking. So the undertow of breaking waves are an important factor in sediment transport offshore.

E.5 Wave-induced set-up

Wave-induced set-up is induced by changes of radiation stress between two locations. Radiation stress is the depth-integrated and wave-averaged flux of momentum due to waves. Due to these changes in radiation stress wave forces act on the fluid and impact the mean water motion and the mean water levels. These wave forces cause the following water motions, shown in figure E.7:

- Set-down: lowering the mean water level in the shoaling zone
- Set-up: raising the mean water level in the surf zone
- Mean current: driving an alongshore current in case of oblique incident waves

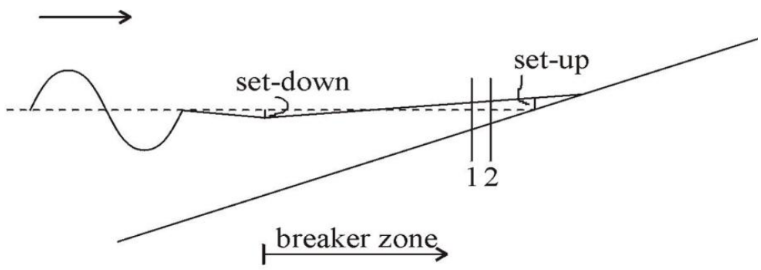


Figure E.7: Set-up and Set-down (Bosboom & Stive, 2015)

In figure E.8 the components of radiation stress are shown for oblique incident waves. Set-down occurs in the shoaling zone: the radiation stress component S_{xx} increases in the positive x-direction (cross-shore direction), the positive gradient of S_{xx} equals a wave force (F_x) in the offshore direction. This force is compensated by an onshore directed pressure force, this pressure force is created by a set-down (lowering the water level). Set-up occurs in the surf zone: the radiation stress component S_{xx} decreases in the positive x-direction (cross-shore direction), the negative gradient of S_{xx})equals a wave force (F_x) in the onshore direction. This force is compensated by an offshore directed pressure force, this pressure force is created by a set-up (raising of the water level towards the water line).

The right panel in figure E.8 illustrates set-down and set-up in a cross-shore beach profile.

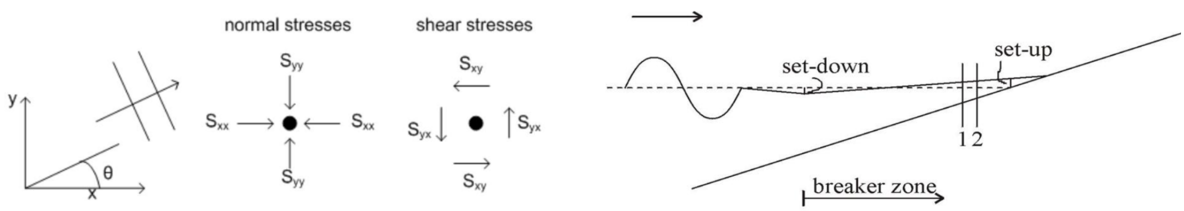


Figure E.8: Left: Radiation stress components; Right: Set-up and Set-down (Bosboom & Stive, 2015)

In the alongshore direction the transfer of momentum from the wave motion to the mean flow gives rise to a alongshore current. The cross-shore rate of variation of the shear component of the radiation stress S_{yx} acts as a driving force. In the cross-shore direction the balancing force was supplied by a hydraulic pressure gradient. But in the alongshore direction no hydraulic pressure gradient can develop. In the alongshore direction the variations of the radiation stress is compensated by bed shear stress, which are generated by a alongshore current. The highest velocities in the alongshore current are found landward of the breaker line.

E.6 Wave-induced currents

In the case of emerged groynes wave diffraction occurs in the lee side of the groynes. Wave set-up is less in sheltered areas near the groynes than the wave set-up in the less sheltered areas between two groynes. This difference in set-up generates local near-shore currents from the unsheltered area towards the sheltered area and towards the groyne. At the groyne the current is diverted outward the groyne field along the groyne, this current pattern is equivalent to an eddy. This current pattern can be seen in figure E.9.

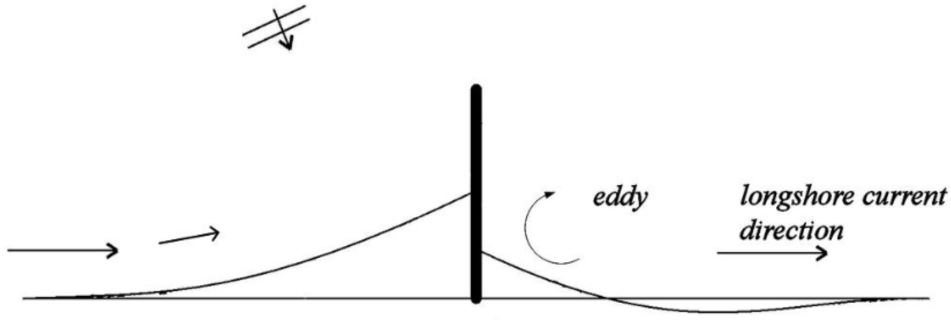


Figure E.9: Near-shore current near groyne (Bosboom & Stive, 2015)

F. Wave morphodynamics

In this appendix sediment transport by waves is elaborated.

The flow velocities in ship waves may induce transport of sediment by the initiation of motion. The velocities due to wave asymmetry, long waves and the return flow together set the sediment in motion in a certain direction.

The flow velocity close to the bed consist of the wave group averaged component, the short wave averaged oscillatory component and the short wave component, given in figure F.1.

$$u = \underbrace{\overline{u}}_{\substack{\text{time-mean component} \\ \text{(streaming outside surf zone,} \\ \text{undertow in surf zone)}}} + \underbrace{u_{lo}}_{\substack{\text{low-frequency motion} \\ \text{at wave-group scale}}} + \underbrace{u_{hi}}_{\substack{\text{oscillatory motion at} \\ \text{short wave scale}}}$$

Figure F.1: Components of the velocity close to the bed (Bosboom & Stive, 2015)

To be able to assess the relative contributions of the components to the net sediment transport (averaged over the wave group), the third odd velocity moment is looked at, which determines the bed load transport. The combination off these third odd moments is given in figure F.2.

$$\left\langle u\left|u\right|^2\right\rangle = \underbrace{3\left\langle \overline{u}\left|u_{hi}\right|^2\right\rangle}_{1} + \underbrace{\left\langle u_{hi}\left|u_{hi}\right|^2\right\rangle}_{2} + \underbrace{3\left\langle u_{lo}\left|u_{hi}\right|^2\right\rangle}_{3} + \ldots$$

Figure F.2: Components of the third odd velocity moment that determines the bed load transport (Bosboom & Stive, 2015)

The term u_{hi} refers to sediment that is stirred up by short waves. Term 1 is related to the subsequent transport by the mean current, the onshore wave-induced near bed streaming in non-breaking waves or offshore undertow in the surf zone for breaking waves. Term 2 is related to the short term skewness and term 3 is related to the interaction between the long wave velocity and the short wave velocity variance.

Term 2 is non-zero and onshore directed, because the larger onshore peak velocities under the wave crests are more effective in stirring up sediment than the smaller offshore velocities under the wave troughs. This is because of the wave become asymmetric during shoaling.

Term 3 is offshore directed until the bound long waves are not yet released from the group and onshore directed from the point the bound long waves become released during breaking of short waves.

In figure F.3 the three components and the total sediment transport are shown for winter conditions. The positive y-values corresponds to onshore directed sediment transport. Term 1 is fully offshore, term two is fully onshore, term 3 is until the breaking point offshore and from the breaking point onshore, the total transport is offshore for winter conditions and the undertow is dominant. For summer conditions term 1 onshore transport occurs due to dominant short wave skewness. This figure shows also that the gross cross-shore transport can be high.

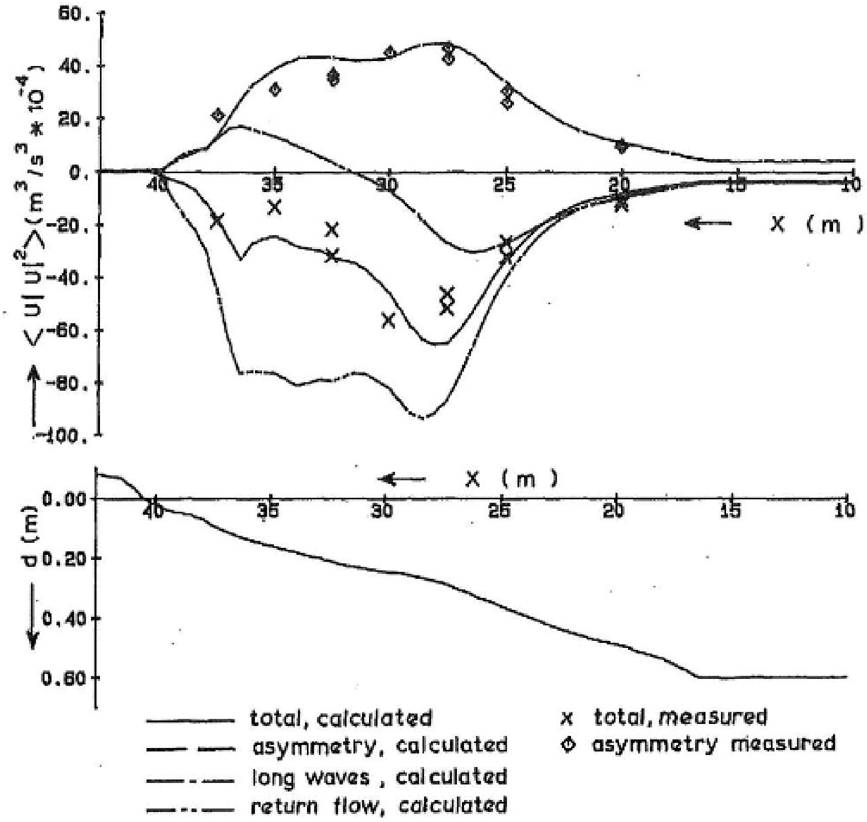


Figure F.3: Components that impact the sediment transport cross-shore (Bosboom & Stive, 2015)

In shallow water the contribution of the wave motion to the bed shear stress magnitude is often more important than the contribution by the mean current. Waves stir up the sediment and currents transport it.

G. Navigation

G.1 Water movement in a groyne field

In figure G.1 the water movement can be seen for the passage of a ship along a smaller groyne field, where only one eddy occurs. The ship is sailing upstream along the south-side of the Waal near Druten.

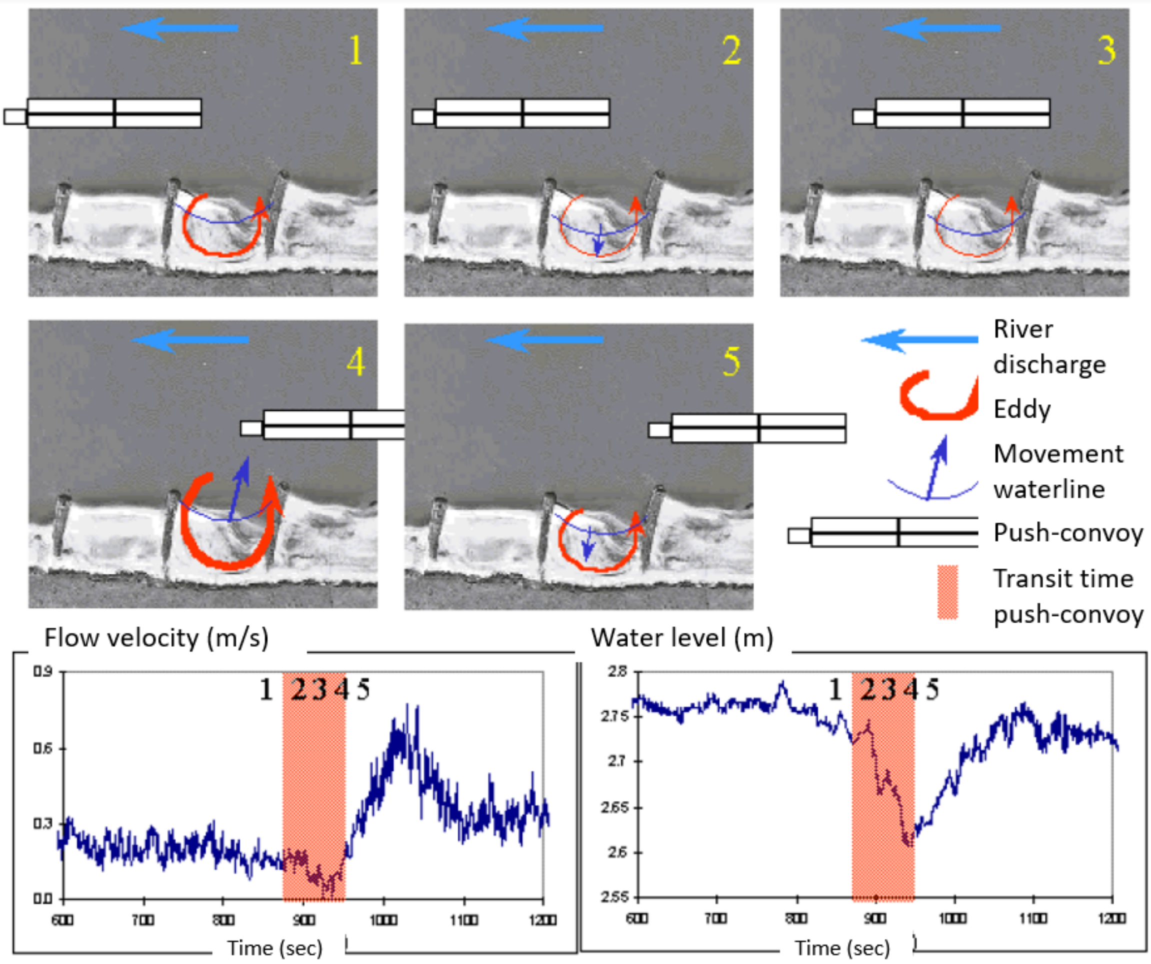


Figure G.1: Water movement in a groyne field during the passage of a ship (Ten Brinke, 2003)

In figure G.2 the water movement can be seen for the passage of two successive ships along a groyne field, the ship is sailing upstream along the south-side of the Waal near Druten.

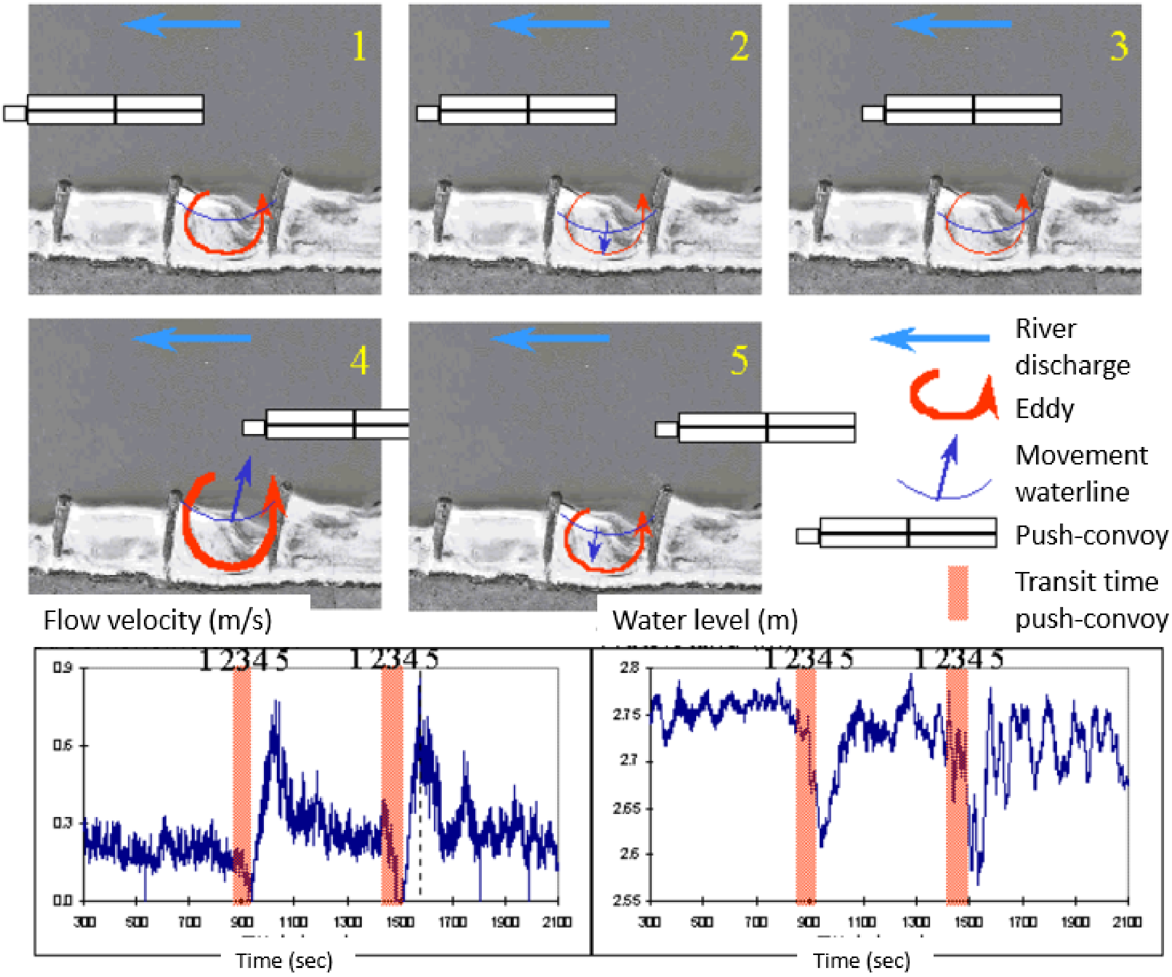


Figure G.2: Water movement in a groyne field during the passage of two successive ships (Ten Brinke, 2003)

H. Software

H.1 XBeach

Xbeach is a depth averaged shallow water flow model, which is developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometres and on the time scale of storms. Later the model has been expanded so it can be applied to other types of coasts and purposes. The model has been validated with a series of analytical, laboratory and field test cases using a standard set of parameter settings (Roelvink et al., 2015).

XBeach has three modes ((Roelvink et al., 2015):

- Stationary model: solving wave-averaged equations efficiently. Infra-gravity waves are neglected. (Moderate wave conditions)
- Surfbeat/instationary model: resolving short wave amplitude variations separately from the long waves, currents and morphological change (phase of the short waves is not simulated)
- Non-hydrostatic model: solves non-linear shallow water equations and takes the phase of the short waves into account. A pressure correction term is applied. Propagation and decay of individual waves can be used.

The model includes the hydrodynamic processes of short wave transformation (refraction, shoaling and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup, unsteady currents, overwash and inundation.

The ship's primary and secondary ship waves can be reproduced in the non-hydrostatic mode by a moving pressure field: the ship is replaced by a pressure field and the movement of the ship is simulated by moving this pressure field at each time step corresponding to the ship's sailing speed.

The morphodynamic processes include bed load and suspended sediment transport, dune face, avalanching, bed update and breaching. Effects of vegetation and hard structures have been included.

H.2 Delft3D

Delft3D is 3D modelling software tool to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments.

The FLOW module is the basis of Delft3D and is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation programme which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid or spherical coordinates (Deltares, 2014).

The MOR module computes sediment transport (both suspended and bed load) and morphological changes for cohesive and non-cohesive material. Multiple sediment transport formulas are included in Delft3D, these transport formulates are based on currents and waves as driving forces. For the suspended load this module connects to the 2D or 3D advection-diffusion solver of the FLOW module.

The MOR module interacts with the the FLOW and WAVE modules, therefore the simulated flows and waves adjust themselves to the local bathymetry. Delft3D can do simulations on a time scale from days (storm impact) to centuries (system dynamics).

H.3 Included processes software

Stokes drift

Stokes drift is included in the hydrodynamics of Delft3D and XBeach, but for both models Stokes drift has no effect on the sediment transport, so it is not included for the morphodynamics (Zimmermann et al., 2015).

Return flow

In both models the return flow is accounted for with the Generalized Lagrangian Mean method (GLM). Here the the depth-averaged velocity, Lagrangian velocity, is the sum of Stokes drift and the Eulerian velocity which is the return flow.

In Delft3D the advection-diffusion equation for suspended transport uses the Lagrangian velocity. The Lagrangian velocity equals zero in cross-shore direction since there is no mean current from and to the coast. Sediment can therefore not be carried offshore by this process in a 2D model.

XBeach overcomes this issue by considering two velocity components for sediment transport. The velocity used in the advection-diffusion equation is the sum of the Eulerian velocity or return flow and an artificial onshore velocity to account for wave non-linearity (skewness and asymmetry) (Zimmermann et al., 2015).

Wave non-linearity (skewness and asymmetry)

In Delft3D, the bed load transport magnitude under waves and currents is calculated from a combined wave and current shear stress according to the method of Van Rijn. The transport direction is then split between the wave component in the direction of wave propagation and the current component in the direction of the current. The effect of wave asymmetry on suspended transport is then added in the bed load component. A correction of transport magnitude and direction for bed slope effects is added to the total bed load vector. The bed load factor scales the streaming component and the suspended load factor scales the skewness component (Zimmermann et al., 2015).

In XBeach wave non-linearity effects are included in suspended sediment transport. Bed load transport is not included, however the bed load and suspended load fractions are determined from coefficients in the equilibrium concentration which are a function of the grain size, the local water depth and the relative sediment density. Bed load and suspended load therefore seem to have the same direction. Wave skewness and asymmetry do not influence the equilibrium sediment concentration, which depends on a combined wave and current shear stress according to the method of Soulsby-Van Rijn (Zimmermann et al., 2015).

In- and exfiltration

Delft3D does not include an in- and exfiltration module. XBeach includes a groundwater module with in- and exfiltration of water according to Darcy's law (Zimmermann et al., 2015).

Gravity

In Delft3D, gravity effects are taken into account with a bed slope correction on the direction and magnitude of the bed load transport.

In XBeach, gravity effects are taken into account with a correction of the equilibrium concentration (Zimmermann et al., 2015).

Turbulence

Both models do not include the effect of wave breaking turbulence.

Wind stress

In both models a wind field can be added to influence the hydrodynamics. Upwelling or downwelling circulation are not incorporated, but the wind could drive the flow alongshore (Zimmermann et al., 2015).

Fall velocity

Both models do not include intrawave lag effects. The fall velocity only appears through the settling time lag added to the advection-diffusion equation for suspended transport (Zimmermann et al., 2015).

Bed forms

In Delft3D the bed roughness can vary in space in two ways:

- Add a file defining the space-varying roughness (constant for the duration of the simulation)
- Use a bed roughness predictor (the bed forms and roughness are computed at every time step from the local hydrodynamic conditions)

Relaxation times determine the time needed for the bed forms to adapt to new hydrodynamic conditions.

In XBeach the space-varying bed roughness can be specified in a input file. Since it is static this option can only be used when time scales of bed form evolution are large compared to the simulation time or for stationary hydrodynamic forcing (Zimmermann et al., 2015).

Long waves

Delft3D does not model long waves, but XBeach does model time-varying long waves. This surf beat is combined to an avalanching law and a robust drying-wetting scheme to produce realistic dune erosion. The avalanching results from the fact that the critical slope of wet sediment is lower than the critical slope of dry sediment. When surf beat reaches the dune foot, the sediment becomes unstable and is redistributed instantly downward until the critical wet slope is reached. This new sediment can then be transported under water by other mechanisms such as the return flow (Zimmermann et al., 2015).

Wave roller

Delft3D includes a model extension for surf beat and wave roller. The wave roller implementation follows a parameterisation instead of a roller energy balance.

XBeach models the wave roller with a roller energy balance. The energy dissipated by breaking waves is the source term of the roller energy, which dissipates again at a rate which depends on the slope of the wave front (Zimmermann et al., 2015).

3D effects

3D effects may include longshore currents, wind circulations, circulation cells and rip channels formed by long waves, such as shear waves and edge waves. XBeach can model these processes.

Delft3D can model longshore currents and horizontal wind circulations, but not processes related to long waves (Zimmermann et al., 2015).

I. Bottom level data

Annually Rijkswaterstaat conducts measurements of the bottom level of the Waal. The focus is on measuring the bottom level of the main channel. Early 2018 a couple of groyne fields were measured near Nijmegen, Sint Andries and Druten. An overview can be seen in figure I.1.

Figure I.1: Overview bottom level data Waal

The groyne field measurements near Nijmegen are done from January 27 until 30 2018, near Sint Andries between January 25 and 31 2018 and near Druten from December 14 2017 until January 16 2018. The main channel of the Waal is measured from April 16 until May 1 2018.

The measurements are done with multi-beam sonars and have a resolution of 1x1 m. For every measured point the RD new coordinates (Rijksdriehoekscoördinaten) and the water depth are given. Characteristics of the RD new coordinate system are:

- Name: Amersfoort / RD New
- Datum: Amersfoort
- Ellipsoid: Bessel 1841
- Prime meridian: Greenwich
- Unit: metre
- Latitude of origin: 52.15616055555555
- Central meridian: 5.38763888888889
- Scale factor: 0.9999079
- False easting: 155000
- False northing: 463000

Nijmegen

In figure I.2 the bottom level of the main channel and the groyne fields near Nijmegen are shown. On the left in the figure the side channel Lent can be seen. Here, also the city of Nijmegen is located.

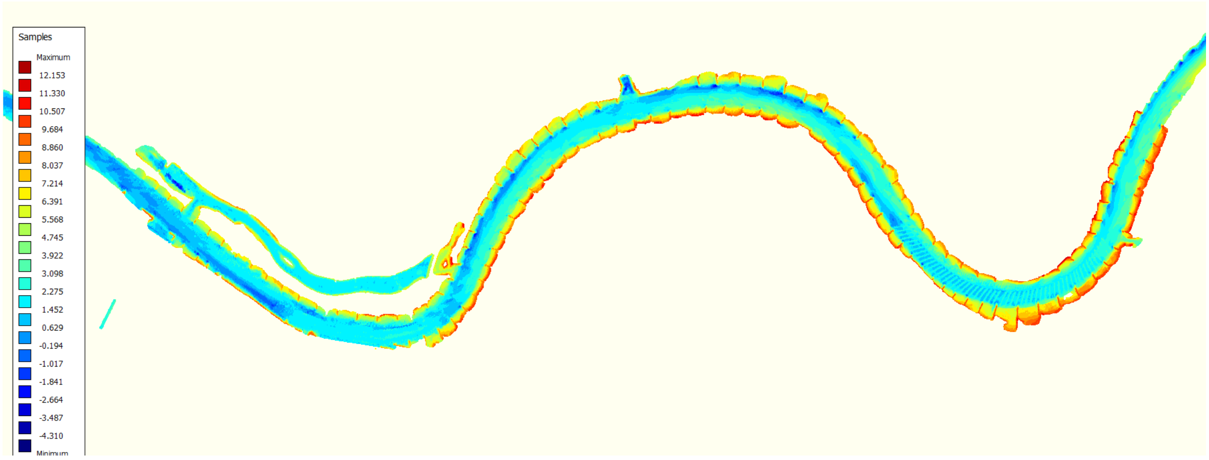


Figure I.2: Bottom level measurements near Nijmegen

Sint Andries

In figure I.3 the bottom level of the main channel and the groyne fields near Sint Andries are shown. As can be seen in the figure, the measurement point density in the main channel is low in comparison with the other measured area's.

Figure I.3: Bottom level measurements near Sint Andries

Druten

In figure I.4 the bottom level of the Waal and the groyne fields near Druten are shown.

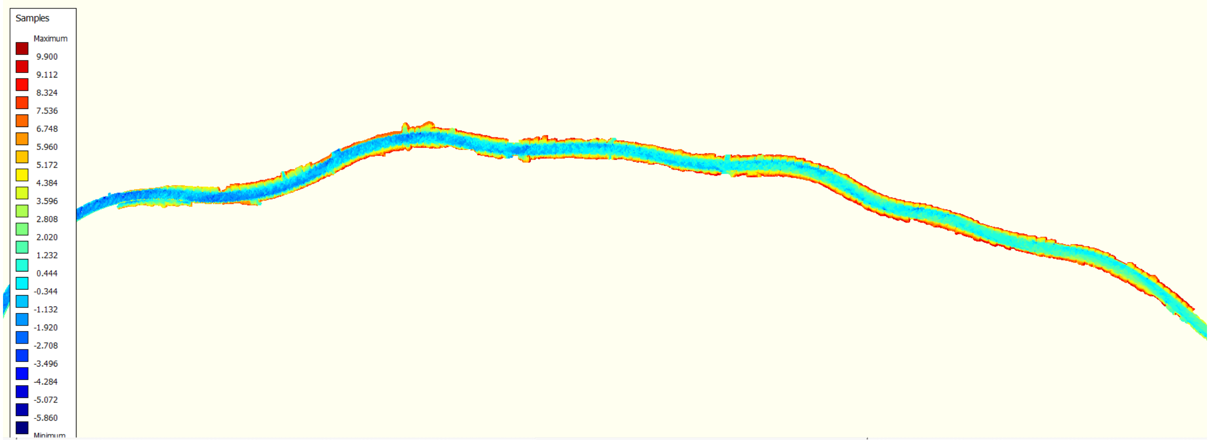


Figure I.4: Bottom level measurements near Druten

J. Model

J.1 Bathymetry

In table J.1 the process of creating a bathymetry from bottom level data for a certain area is given. When the grid is refined also a refined depth profile is made and the same process according to J.1 is used every time.

Table J.1: Step-by-step plan for creating the bathymetry

	What	**Software tool**	**Description**
1	Analysing the bottom level data of the research location from the bottom level data of the Waal	Delft3D -RGFGrid	The available bottom level data is visualised and the exact coordinates of the research location are looked up
2	Creating a depth sample from the bottom level data for the research location	Python	Extracting the bottom level data from the total data set by writing a Python script, which takes x and y coordinates as input
3	Creating a bathymetry	Delft3D -Quickin	Based on the depth sample and the grid a .DEP file is created by using grid cell averaging, triangular interpolation and internal diffusion

J.2 Sediment in the Waal

The Waal is a sand river, this means that the top layer of the river bottom consists of coarse sediment. In figure J.1 the grain size distribution is given for the Waal. At 0 on the x-axis is the Pannerdensche Kop located, so there the Rhine splits into the Pannerdensch Kanaal and the Waal. Going downstream, gravel is replaced by coarse sand. Coarse sand has a median grain size of about 2mm (Ten Brinke, 2004). At 43 km downstream of the Pannerdensche Kop the research location is located.

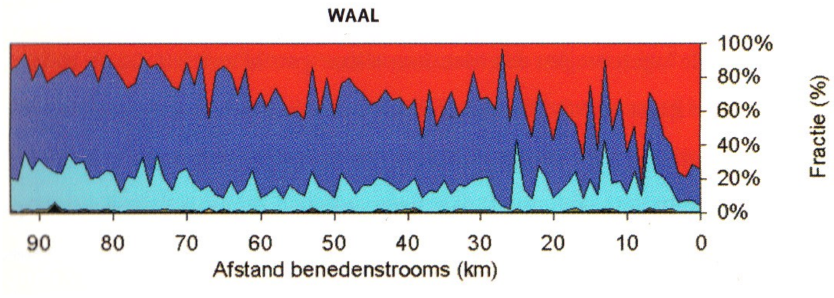


Figure J.1: Grain size distribution of the top 10 cm layer of the Waal; red = gravel, dark blue = coarse - very coarse sand, blue = moderately coarse sand, green = moderately fine sand (Ten Brinke, 2004)

The grain diameters of the sediment in the Waal is shown in figure J.2, D_{50} gives the the grain diameter for which 50% of the total weight of sediment has a smaller diameter. The same principle holds for D_{90} and D_{10}.

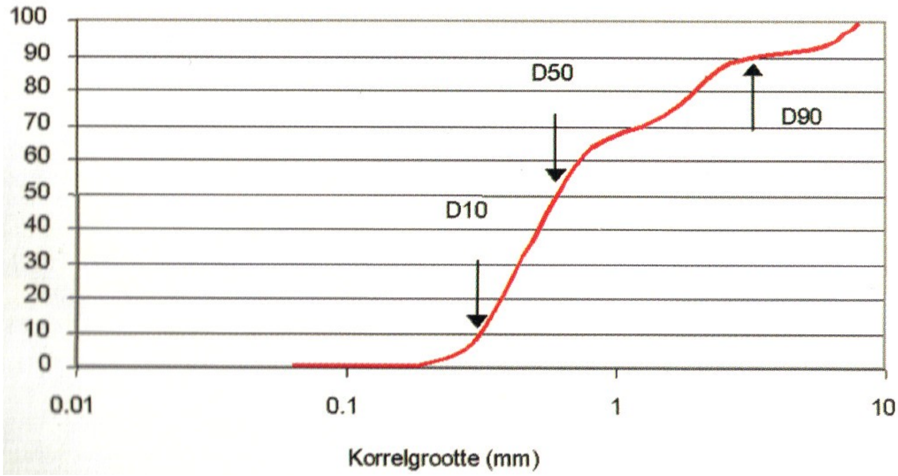


Figure J.2: Mean grain size distribution of the Waal; y-axis represents the percentage of total weight sediment (Ten Brinke, 2004)

From the Upper Rhine sediment is supplied by bottom transport and suspended transport. Gravel and coarse sand are transport by bottom transport. This type of transport is only possible when the discharge of the river is large enough. Fine sand is transported by suspended transport, because the sand is light enough to be picked up from the bottom by the water flow. This type of transport is possible for all discharge levels. Per year about 760,000 ton (510,000 m^3) gravel and sand and 1,660,000 ton fine sand is supplied to the Waal. During high water 250,000 ton gravel and sand is transport into the Waal. These numbers are based on the average over a period of 20 years (Ten Brinke, 2004).

For the morphology in the Waal gravel and sand are of greater importance than fine sand. Fine sand washes through the Waal and will settle in the downstream branches of the Waal: Hollandsch Diep.

J.3 Navigation on the Waal

Each year around 120,000 inland vessels sail on the Waal, therefore the Waal confirms to the intensity profile set up by Rijkswaterstaat (Koedijk et al., 2017). The intensity profile requires multi-lane traffic to provide sufficient transport capacity.

To classify inland waterways in Western Europe the CEMT-classification is set-up. The class of a river defines the largest ship for which the dimensions of the ship are suitable to sail in a certain waterway. The Waal has a VIc classification which defines the maximum ship dimensions by a push convoy. In table J.2 the maximum dimensions are given for the VIc class and in figure J.3 the type of push convoys that belong to this class are shown.

Table J.2: Maximum dimensions CEMT-class VIc (Koedijk et al., 2017)

	Length (m)	Beam (m)	Draught (m)	Tonnage (t)	Minimum height under bridges (m)
2x3	270 - 280	22.80	2.50 - 4.50	9600 - 18,000	9.10
3x2	193 - 200	33.00 - 34.20	2.50 - 4.50		

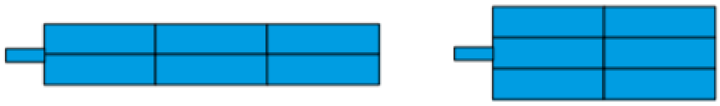


Figure J.3: CEMT-class VIc type of convoy; Left: 2x3; Right: 3x2. (Koedijk et al., 2017)

The maximum ship dimensions allowed on the Waal are given by defining the maximum push-convoy dimensions. Next to the push-convoys also lots of motor ships are sailing on the Waal. Motor ships occur more frequently on the Waal in comparison to push convoys, but the effect of push convoys on the morphology is bigger. For these two types of ships an variant can be seen in figure J.4.

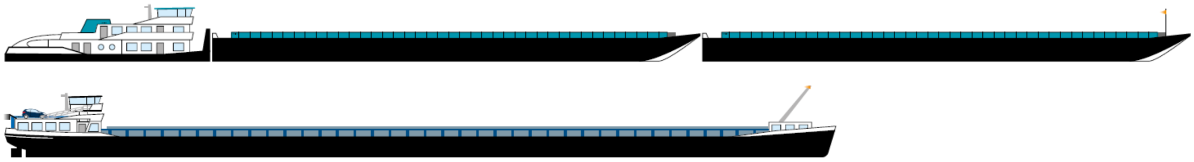


Figure J.4: Top: push convoy; Bottom: motor ship (*Waardevol Transport*, 2017)

K. Elementary model test

In this appendix the elementary model test is described.

K.1 Navigation

In figure K.1 two location are given: one in the main channel and one in the centre of the groyne field. These two location are used in the following to verify the model.

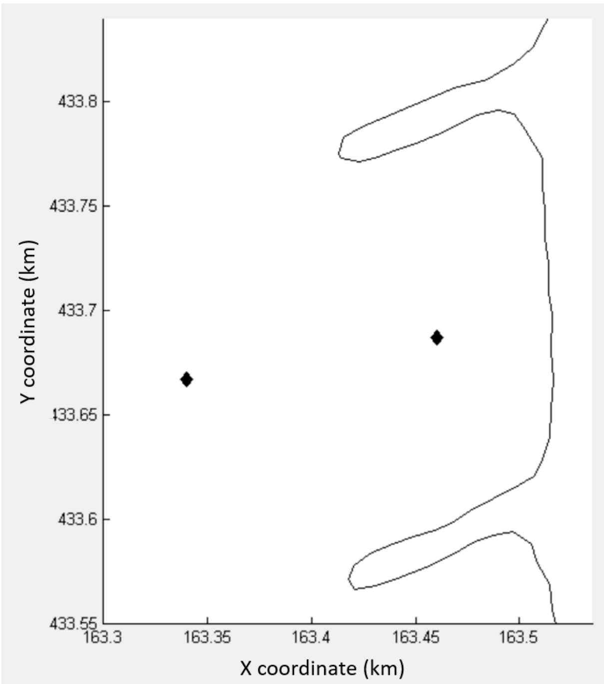


Figure K.1: Locations verification points

Water level

The verification is first done for forcing situation 1 (see table 4.8) thereafter forcing situation 2 and 3 will shortly be verified.

The water level in the main channel can be seen in figure K.2. The blue line gives the results at a grid of 10 x 10 m and the red line gives the results at a grid of 5 x 5 m. The primary wave system can be observed: the increase of the water level with respect to the still water level (3.5 m) at time 0:01:00 is the front wave. At time 0:02:00 the water level depression passes the observation, which is followed by the stern wave at time 0:02:45. The primary wave system should be followed by the secondary wave system, this can only be seen for the 5 x 5 m grid. When the ship has passed the point the water level should go back to the still water level. For both grid sizes large deviations from the still water level are observed and it seems that water level is not travelling back to the still water level.

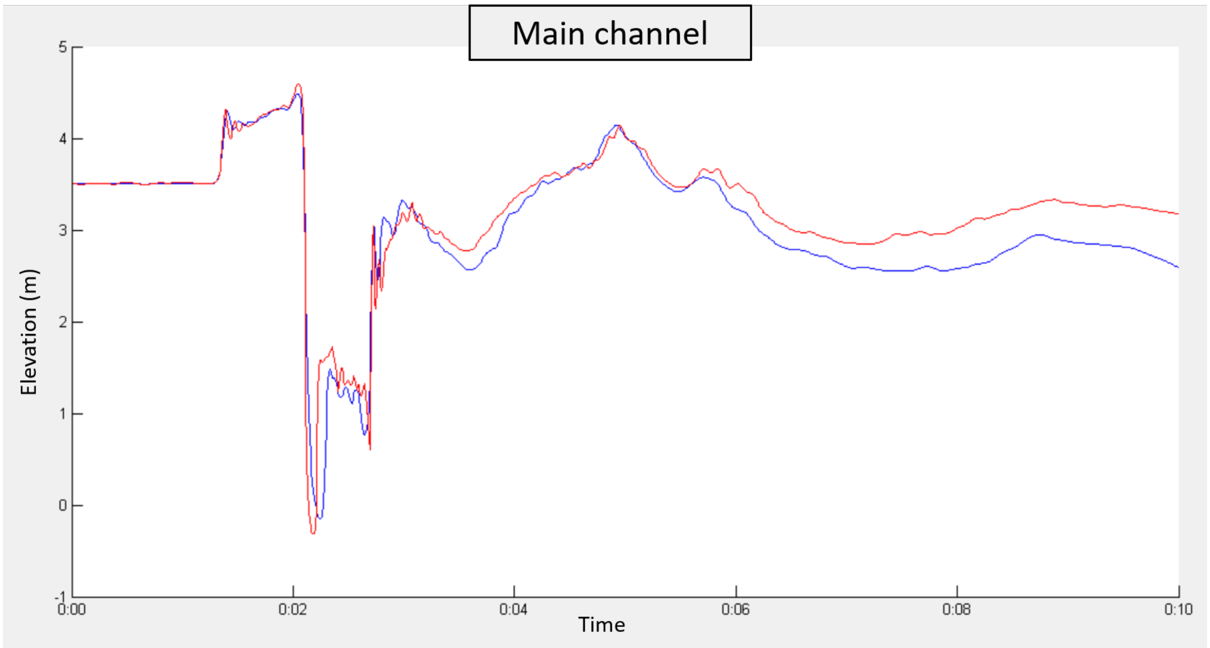


Figure K.2: Water level in the main channel in the case of low water level; Blue line: grid size of 10 x 10 m; Red line: grid size of 5 x5 m;

The water level in the centre of the groyne field can be seen in figure K.3. The blue line gives the results at a grid of 10 x 10 m and the red line gives the results at a grid of 5 x 5 m. At time 0:01:40 a water level increase due to the incoming front wave induced by the passing ship is observed. Comparing the water level peak with the water level measurements from literature, this peak is relatively flat and wide and does not significantly change when the grid is refined. After the water level peak a water level depression can be seen. After the ship has passed the water level fluctuates, which corresponds to figure 2.16. But in the end the water level should go back to the still water level, it seems that this is not happening for both grid sizes.

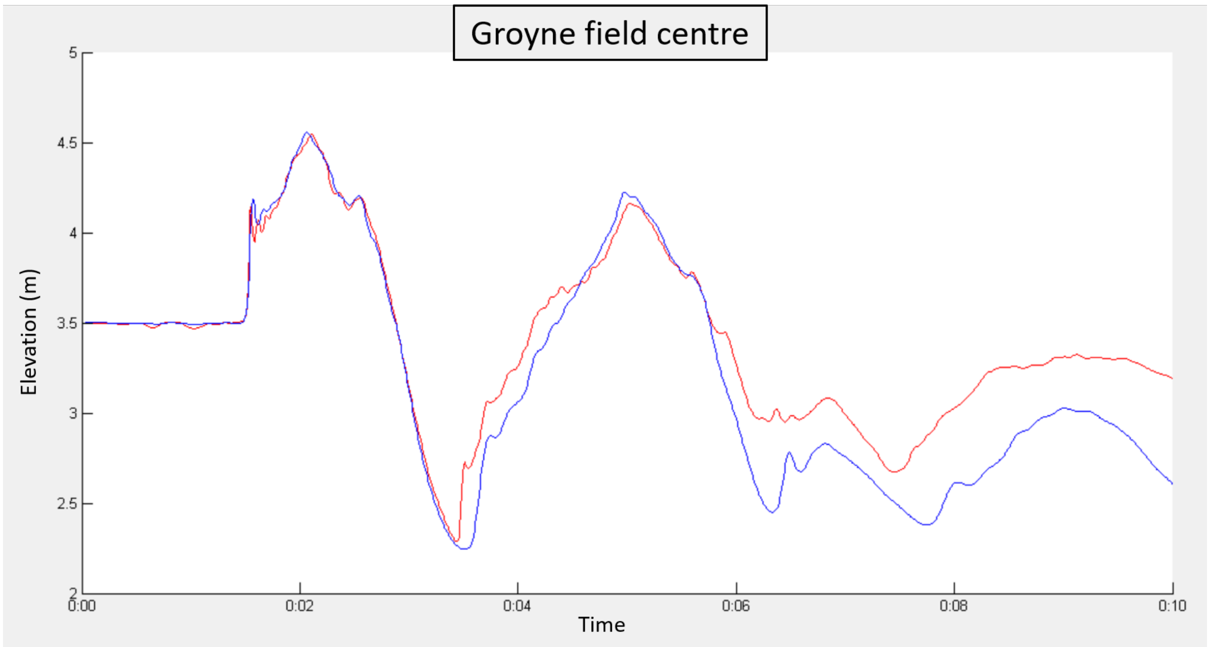


Figure K.3: Water level in the centre of the groyne field in the case of low water level; Blue line: grid size of 10 x 10 m; Red line: grid size of 5 x5 m;

To further improve the results to be able to see quicker damping out of the water level fluctuations, the horizontal viscosity is changed, three values are assess:

- Default value of XBeach: 0.1 m^2/s
- Maximum value that has an effect on the results: 0.5 m^2/s (Zhou et al., 2013)
- Intermediate value: 0.25 m^2/s

The water level in the main channel can be seen in figure K.4. The default value is used for when calculating the previous outputs, so this value is used as reference (blue line). The green line gives the result for a horizontal viscosity of 0.5 m^2/s and the red line gives the result for a horizontal viscosity of 0.25 m^2/s. For all values the primary and the secondary wave system are visible. For the horizontal viscosity's of 0.25 m^2/s and 0.5 m^2/s the water level travels back to the still water level and the water level deviations after the ship has passed are smaller. Since it is realistic that the water level fluctuates a value of 0.25 m^2/s for the horizontal viscosity seems the best choice.

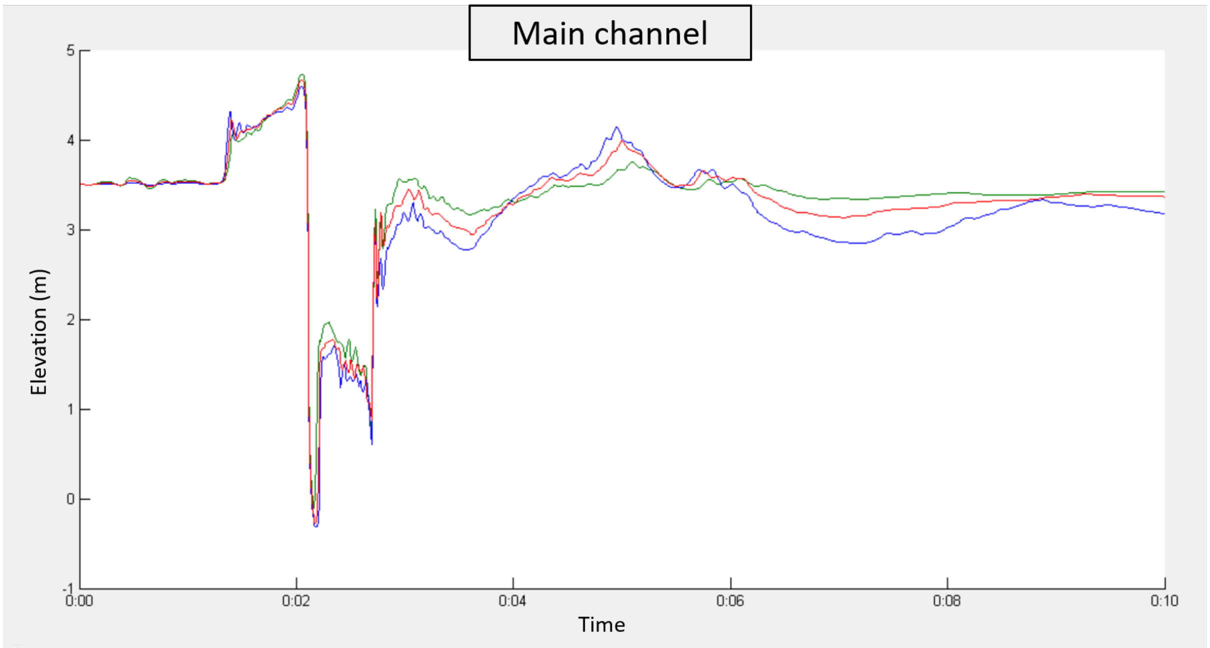


Figure K.4: Water level in the main channel in the case of low water level; Blue line: horizontal viscosity of 0.1 m^2/s; Green line: horizontal viscosity of 0.5 m^2/s; Red line: horizontal viscosity of 0.25 m^2/s;

The water level in the centre of the groyne field can be seen in figure K.5. Also for this location a horizontal viscosity of 0.25 m^2/s seems to give the most realistic results.

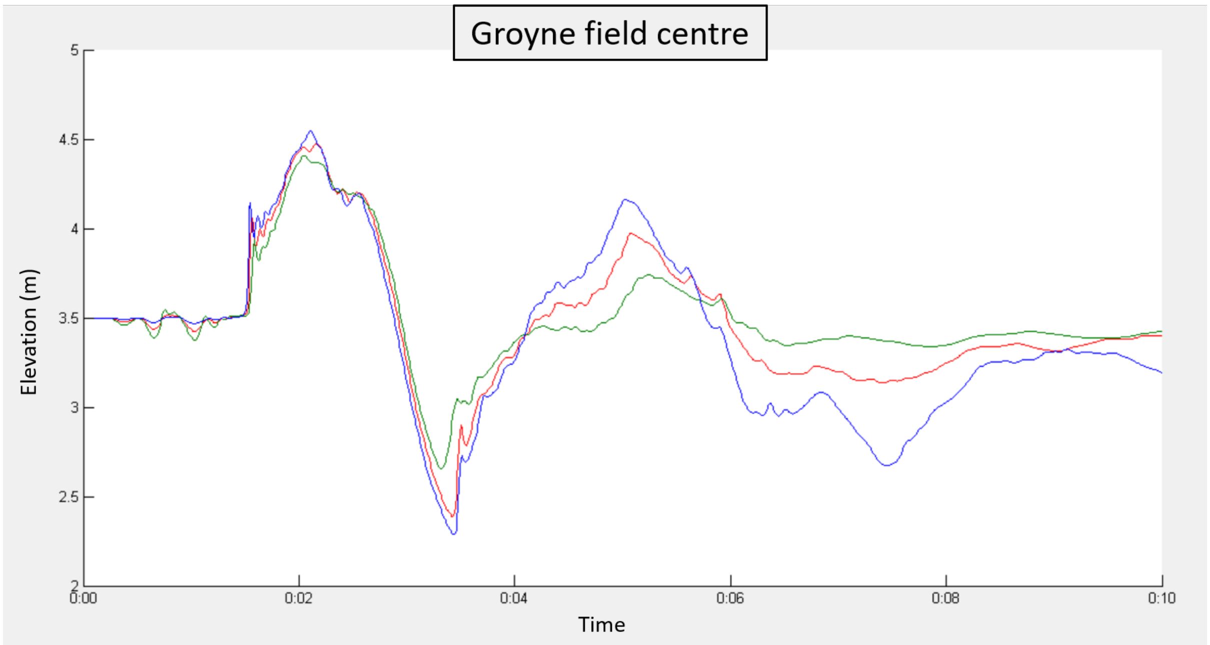


Figure K.5: Water level in the centre of the groyne field in the case of low water level; Blue line: horizontal viscosity of 0.1 m^2/s; Green line: horizontal viscosity of 0.5 m^2/s; Red line: horizontal viscosity of 0.25 m^2/s;

The base model adjustments (grid of 5 x5 m and a horizontal viscosity of 0.25 m^2/s) will be applied to the model of forcing situation 2 and 3.

The water level in the main channel during middle water level can be seen in figure K.6. The primary and secondary wave system are visible and the water level fluctuations seem realistic, lastly the water level travels to the still water level. The secondary waves are better visible since they damp out slower. This seems logical since the cross section changes for a higher water level and the water depth is higher. The results for scenario 2 seem realistic, so no further adjustments to the model are made.

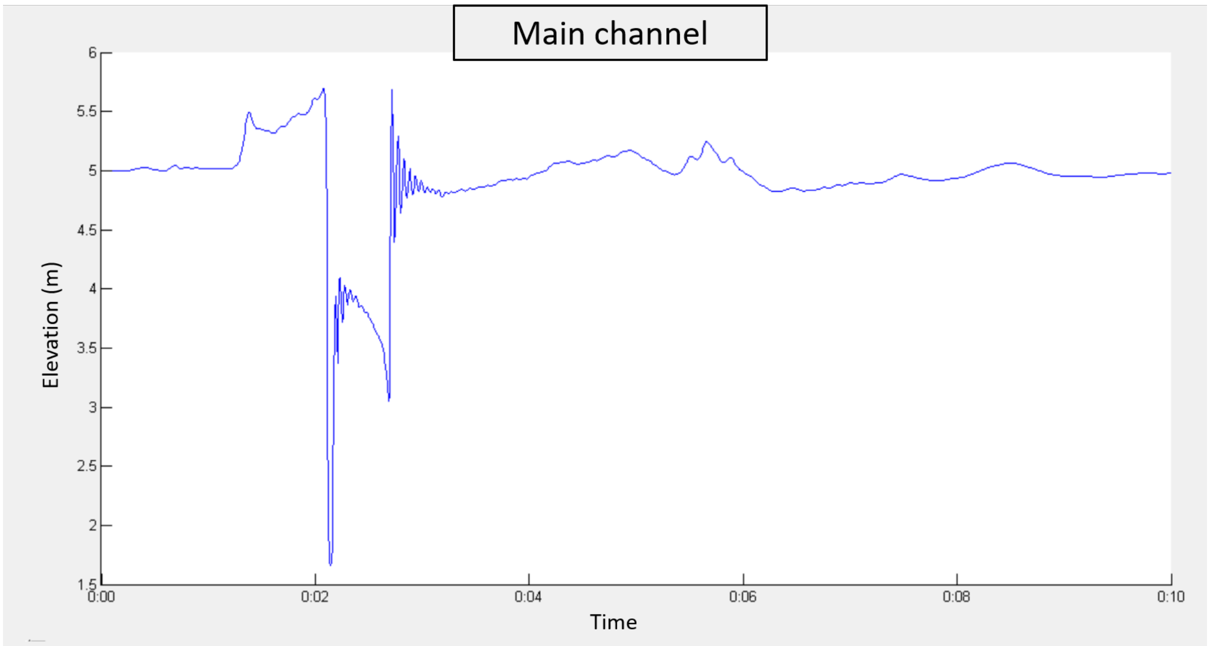


Figure K.6: Water level in the main channel in case of middle water level

The water level in the main channel during high water level can be seen in figure K.7. The primary and secondary wave system are visible and the water level fluctuations seem realistic, lastly the water level travels to the still water level. The secondary waves more pronounced in comparison to the ship waves at low and middle water level. Again the cross section is changed and the water depth is increased, so the secondary waves are less damped. Also the results for scenario 3 seem realistic, so no further adjustments to the model are made.

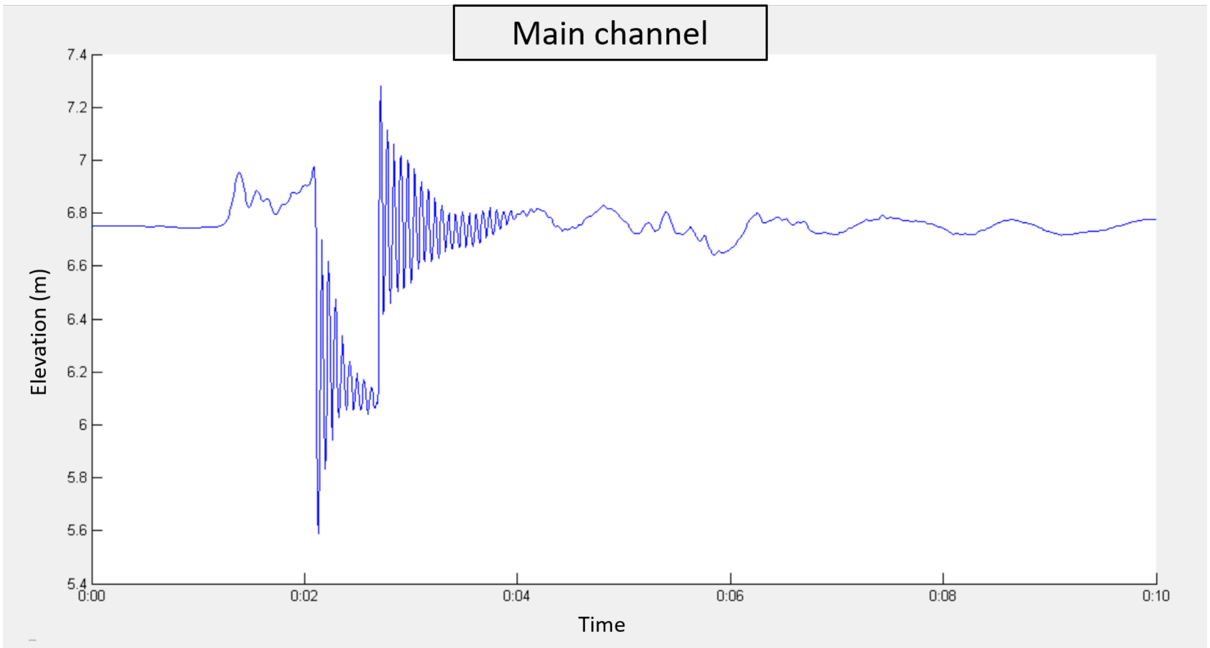


Figure K.7: Water level in the main channel during the passage of a ship in the case of high water level

K.2 River discharge

Stability

First the results of the base model will be discussed followed by some adjustments to the model to improve the results. This model improvement process will be done for forcing situation 4. Thereafter the same adjustments are applied to the model of forcing situation 5 and 6 and the results are checked.

When looking at the water level data of Rijkswaterstaat (measured every 10 min) it is natural that the water level fluctuates around an equilibrium. The deviation is in the order of 1 to 2 cm. So this marge is taken into account when assessing the results. Furthermore the model will develop to a water level corresponding to the discharge, this water level should be not too far from the input water level. The time to evolve to the, more or less, equilibrium water level is called the spin-up time. It is taken into account that the model will never get fully stationary. Per scenario the results are assessed based on usefulness and whether they are realistic.

The model will be run for 24 hours, such that the model has time to spin-up and to see if the model stays stable over a longer period of time. A time step of 10 minutes is taken.

The stability of the model is checked by the water level results along the normal line of the groyne field: main channel (blue line), edge of groyne field (red line), centre of groyne field (green line). The water level at these points are given in figure K.8. It can be seen that the spin-up time is about 7 hours and the equilibrium water level is about 3.27 m in the main channel and 3.31 m in the groyne field. This water level differs too much from the input water level. The water level deviates from the equilibrium water level, this seems to be within the margin of 2 cm. Furthermore it can be seen that the model stays stable after 7 hours.

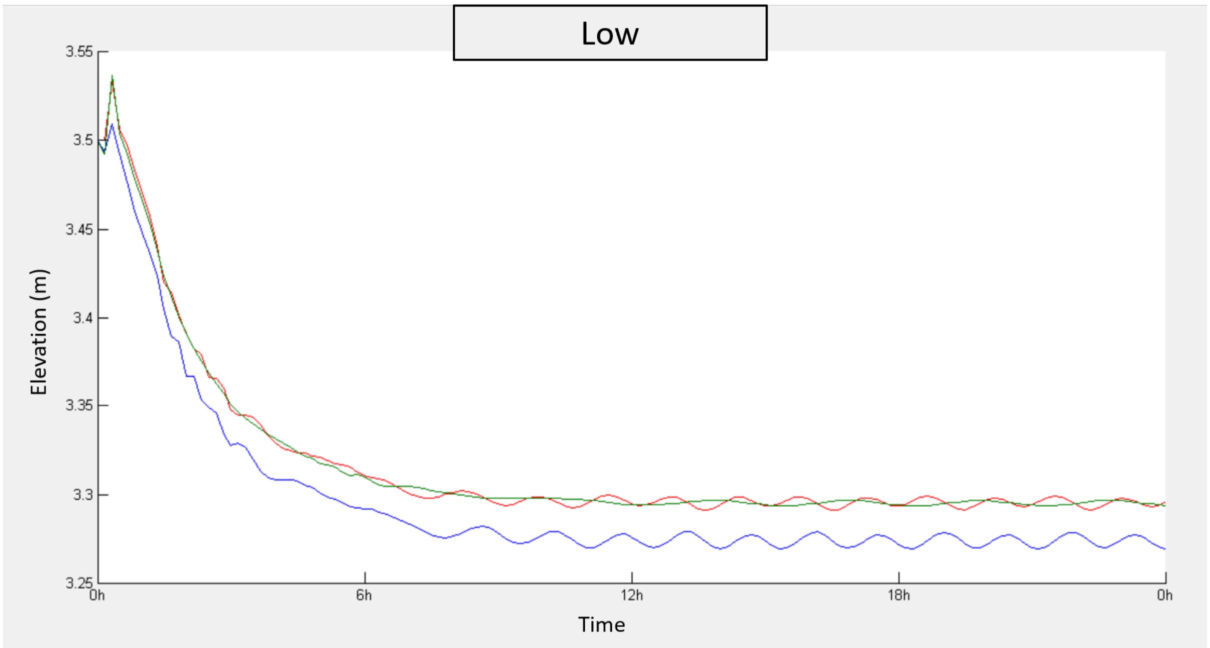


Figure K.8: Water level for low flow conditions

Next, as input to the base model forcing situation 5 is applied. The model time is 24 hours and a time step of 10 minutes is taken. The water level at the three points are given in figure K.9. It can be seen that the spin-up time is about 30 minutes and the equilibrium water level is about 5.05 m for the first 8 hours. This water level does not differ much from the input water level. The water level deviates from the equilibrium water level, this seems to be more than 2 cm so that should be less. Furthermore it can be seen that the model stays more or less stable for 8 hours, thereafter the model slowly and later on quickly develops to a unstable model.

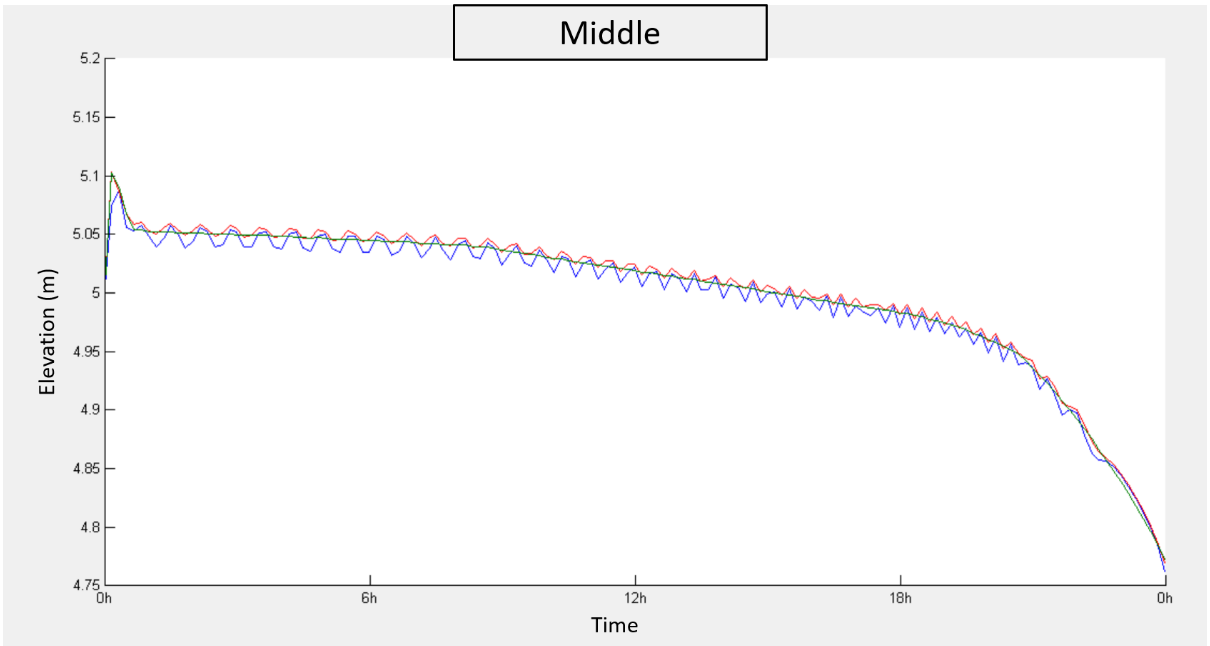


Figure K.9: Water level for middle flow conditions

Lastly, as input to the base model forcing situation 6 is applied. The model time is 24 hours and a time step of 10 minutes is taken. The water level at the three points are given in figure K.10. It can be seen that the spin-up time is about 4 hours, so that is too much. The equilibrium water level is about 6.63 m in the main channel and about 6.65 m in the groyne field, the difference may be explained by the relative high flow velocity difference between the main channel and the groyne field. The equilibrium water level stays close to the input water level. The water level deviations from the equilibrium water level does not stay within the given margin of 2 cm. Furthermore it can be seen that the model stays more or less stable after the spin-up time, but the water level in the main channel has a decreasing trend.

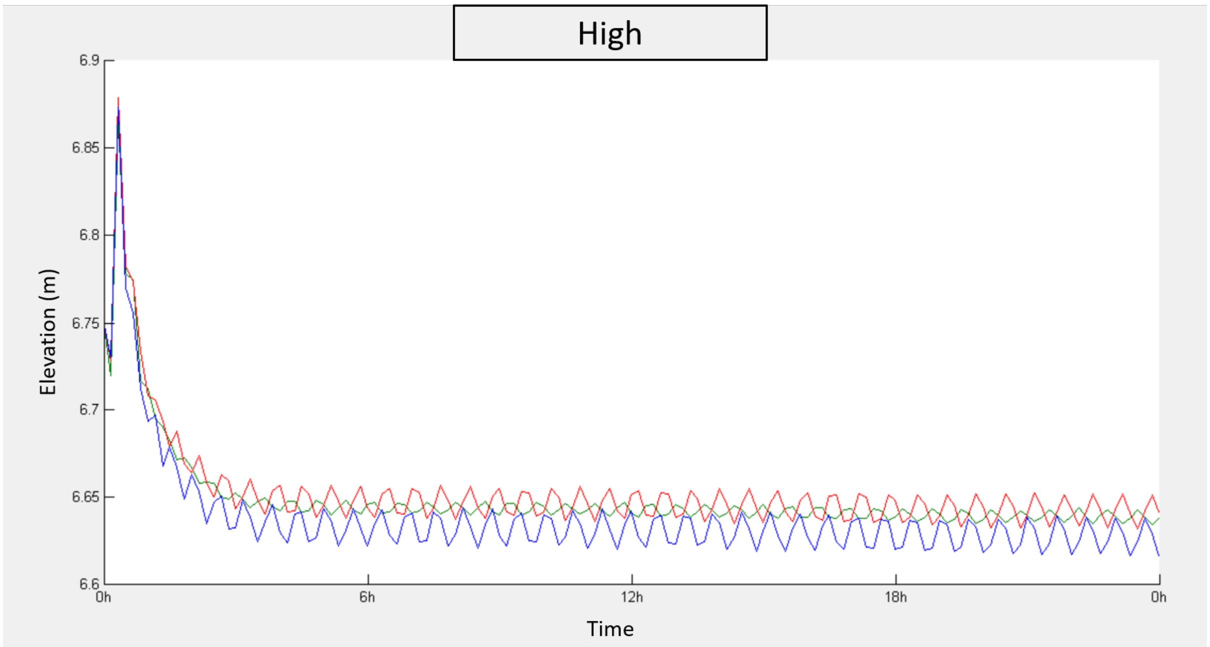


Figure K.10: Water level for high flow conditions

From these results it can be concluded that the spin-up time should be decreased and that the water level deviations from the equilibrium water level should be smaller. Furthermore, when the river discharge needs to be simulated in combination with the ship waves by XBeach a smaller time step is needed. Therefore the stability is assessed when a time step of 0.5 s is used and a horizontal viscosity of 0.25 m^2/s. The results for the three forcing situations are shown in the following.

The water level for forcing situations 4 can be seen in figure K.11. It can be seen that the spin-up time is much longer, about 4 hours, but thereafter the model seems stable and no signs can be found that the model becomes unstable after 24 hours. Furthermore the water level deviations from the equilibrium water level stay within the given marge. The equilibrium water level is decreased to a value of about 3.43 m in the main channel and 3.45 in the groyne field. The difference may be explained by the fact that relative large part of the discharge is flowing through the main channel in comparison to the other flow conditions. This water level decrease is acceptable for scenario 4 (simulating the situation of emerged groynes).

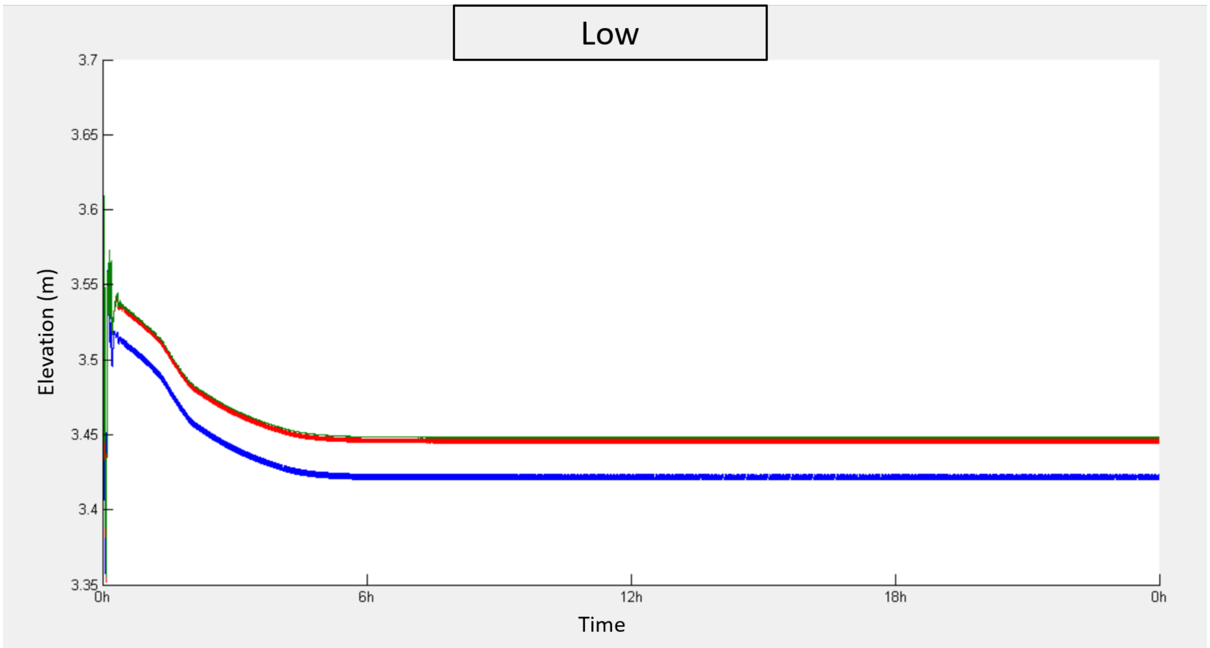


Figure K.11: Water level for low flow conditions

The water level for forcing situations 5 can be seen in figure K.12. It can be seen that the spin-up time is much longer, about 4 hours, but thereafter the model seems stable and no signs can be found that the model becomes unstable after 24 hours. Furthermore the water level deviations from the equilibrium water level stay within the given marge. The equilibrium water level is increased to a value of about 5.25 m, this is acceptable for scenario 5 (simulating the situation of submerged groyne with low submergence level).

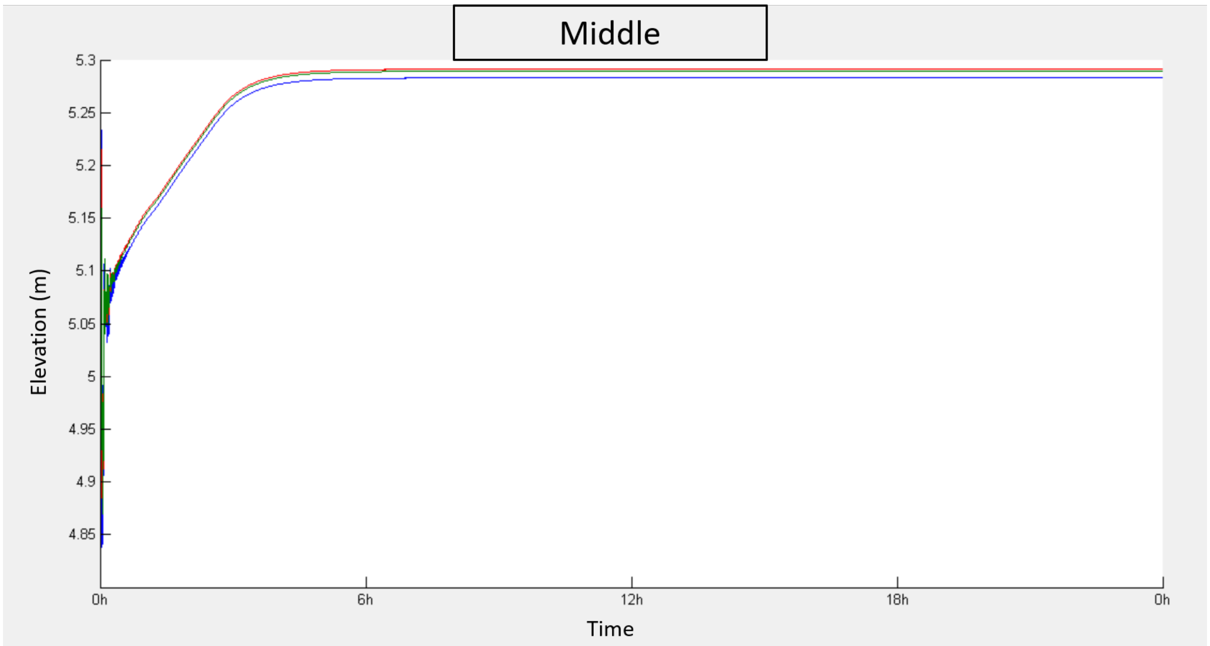


Figure K.12: Water level for middle flow conditions

The water level for forcing situations 6 can be seen in figure K.13. It can be seen that the spin-up time decreased compared to the previous results of scenario 6, the spin-up time is about 3 hours. The equilibrium water level is about 6.65 m, which is close to the input water level. The water level deviations from the equilibrium water level stay within the given marge. Furthermore it can be seen that the model stays stable after the spin-up time and no signs can be found that the model becomes unstable after 24 hours.

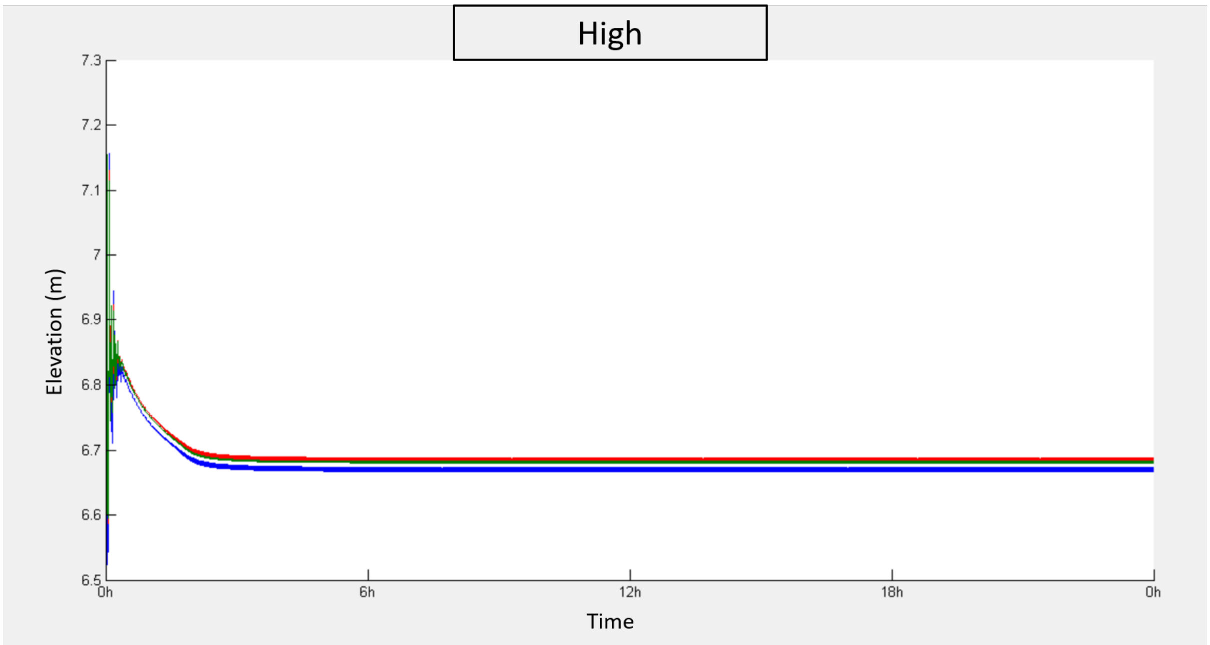


Figure K.13: Water level for high flow conditions

To be able to simulate primary, secondary waves and the river discharge a smaller grid of 5 x 5 m is needed. Due to the large computation times, this runs are done for 6 hours modelling time. A time step of 0.5 s is chosen and a horizontal viscosity of 0.25 m^2/s. The corresponding results for scenario 4 until 6 can be seen in figure K.14 until K.16, respectively. It is clear that these models are not stable and not useful for the next steps of the research. Large computational times does not allow to search for a possible stable model by adjusting model parameters and input.

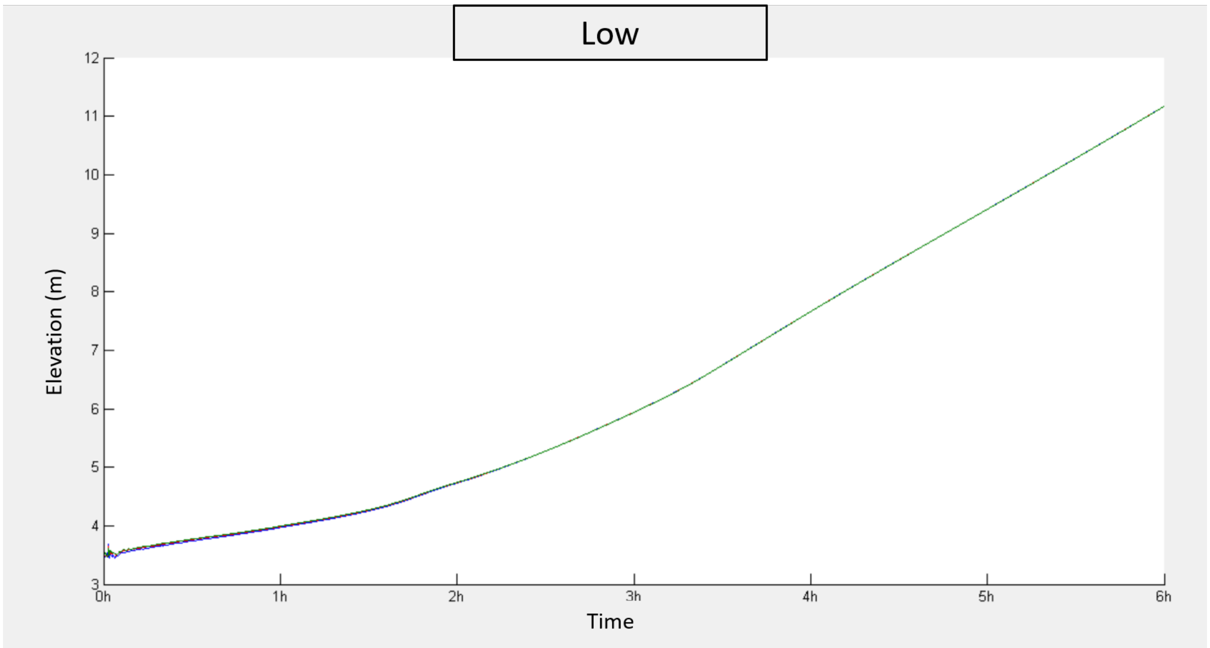


Figure K.14: Water level for low flow conditions

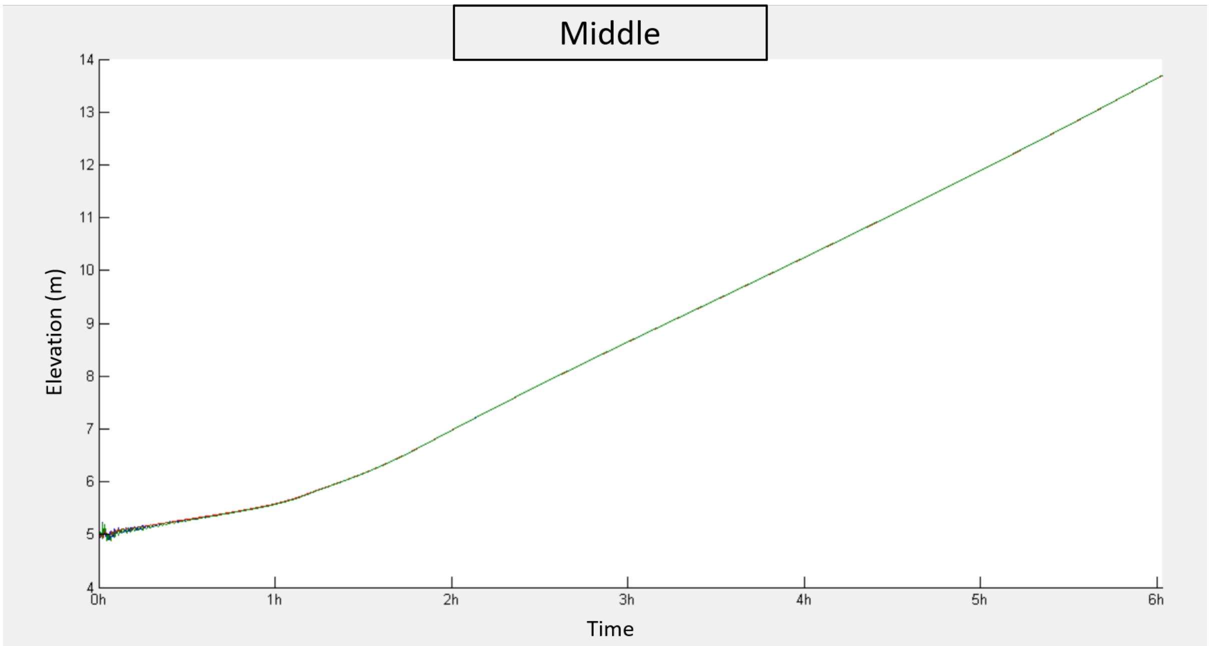


Figure K.15: Water level for middle flow conditions

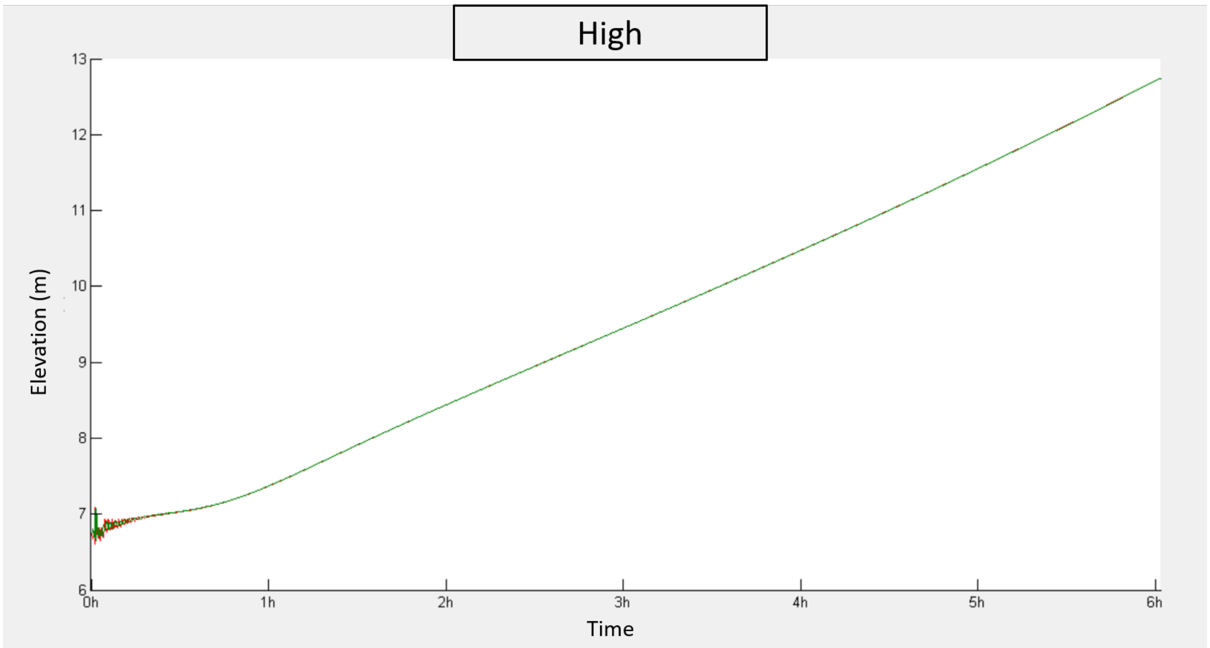


Figure K.16: Water level for high flow conditions

L. Model validation

L.1 Navigation

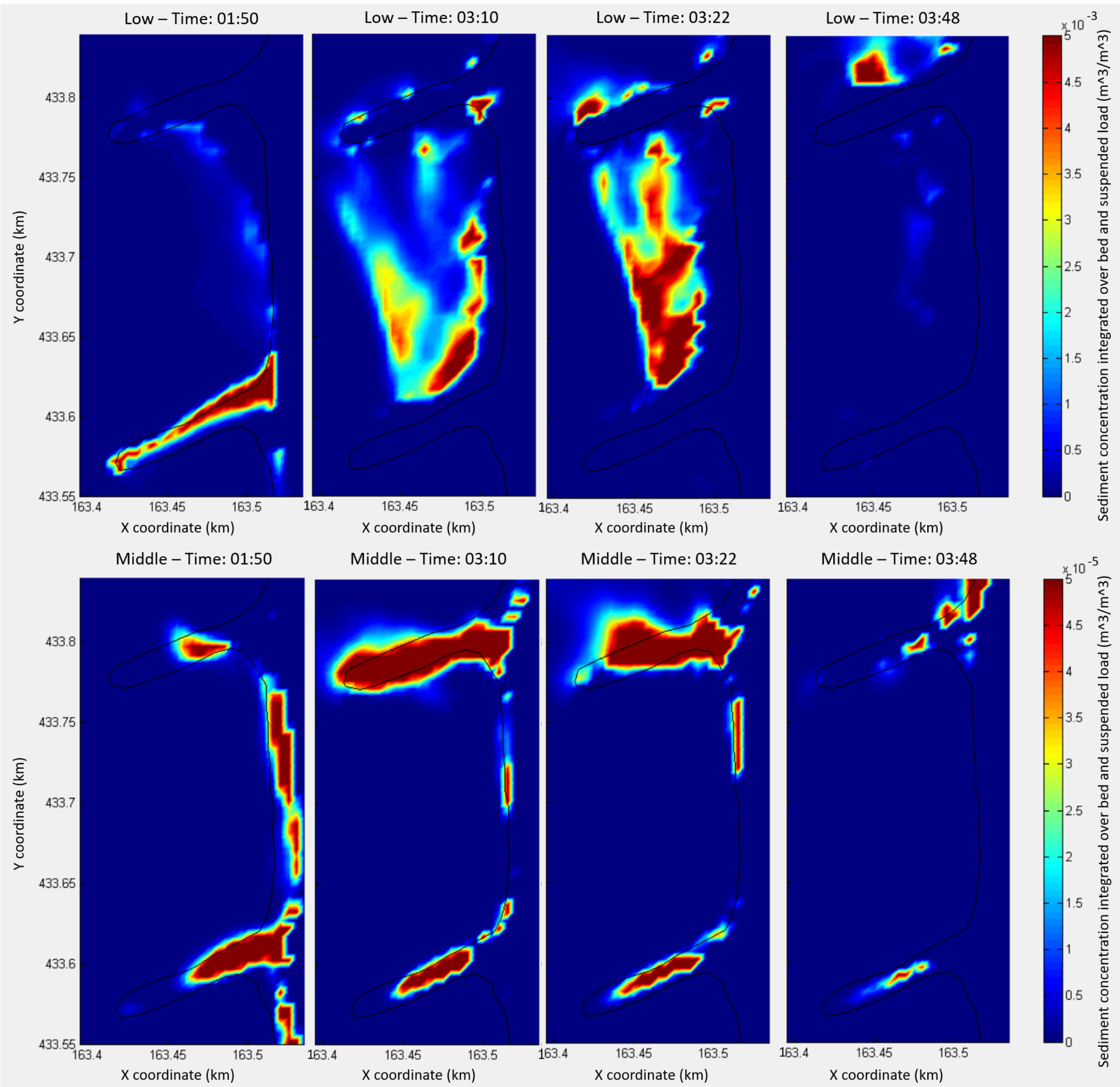


Figure L.1: Sediment concentration during the passage of a ship; Top: low water level; Bottom: middle water level;

M. Model results

M.1 Navigation, no river discharge

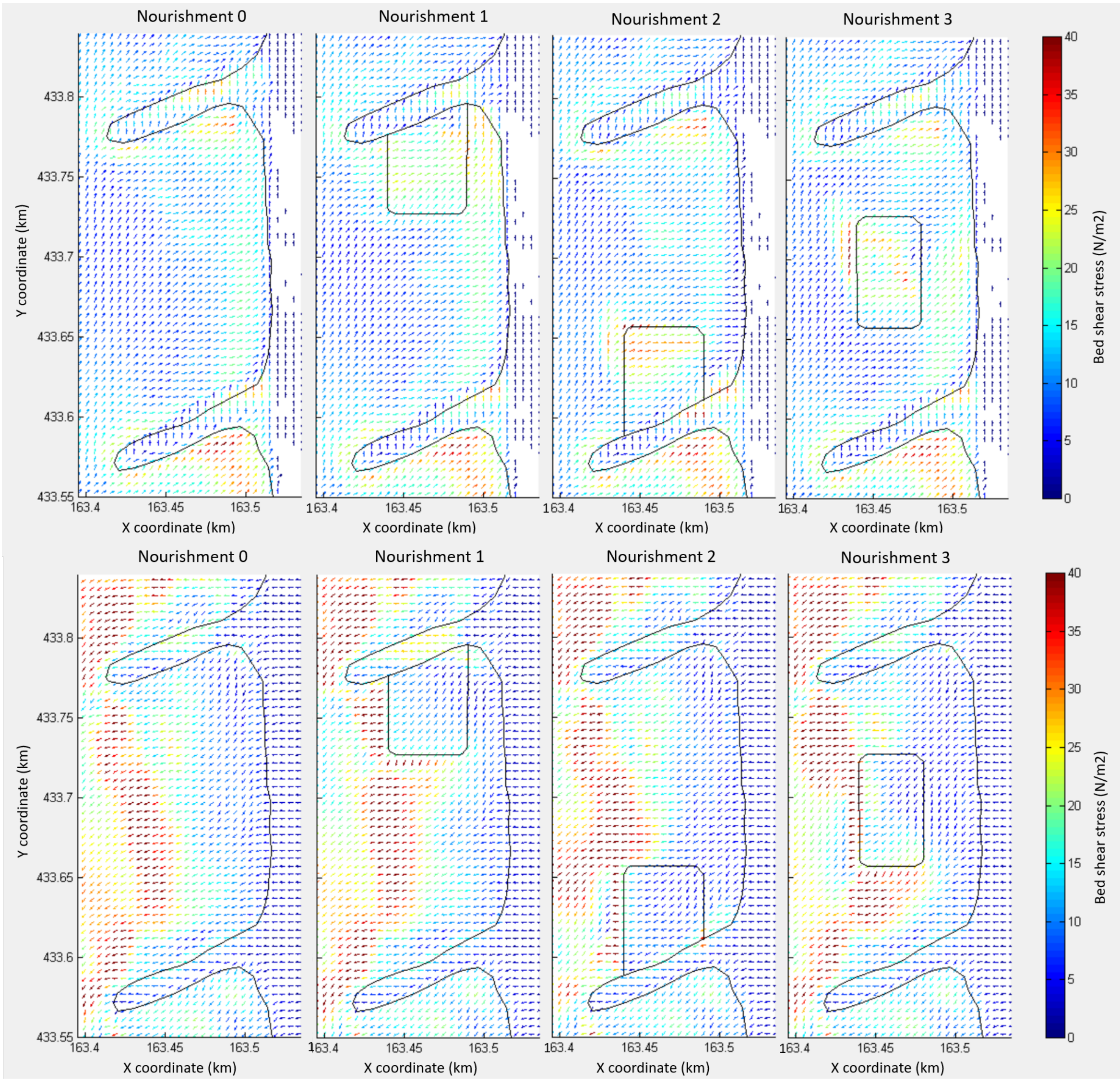


Figure M.1: Top: Max. Bed shear stress when the groyne field is filled during the passage of a ship; Bottom: Max. Bed shear stress when the groyne field is emptied during the passage of a ship

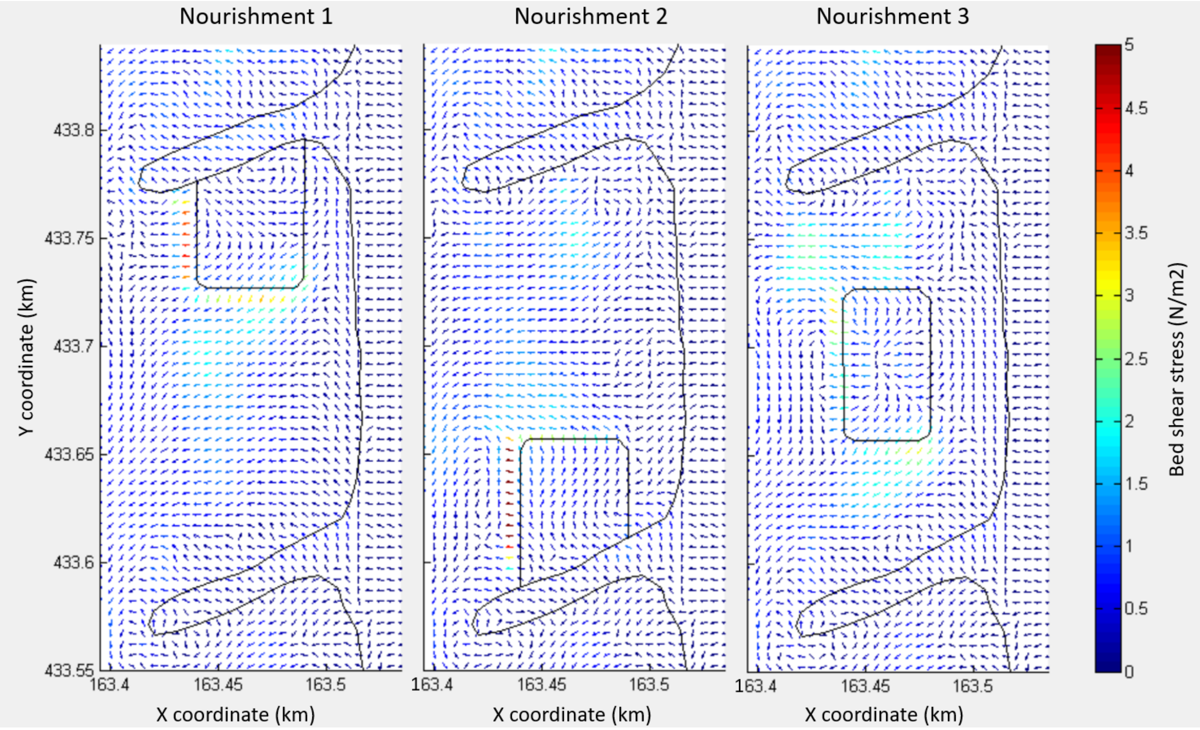


Figure M.2: Mean bed shear stress nourishments in case of navigation and no river discharge

Where the bed shear stress is equal to or higher than 1.30 N/m^2 sediment is brought in motion. The sediment concentration will increase at the locations. Were large colour differences are visible in figure M.2 it is expected that there gradients in sediment concentration lead to sediment transport.

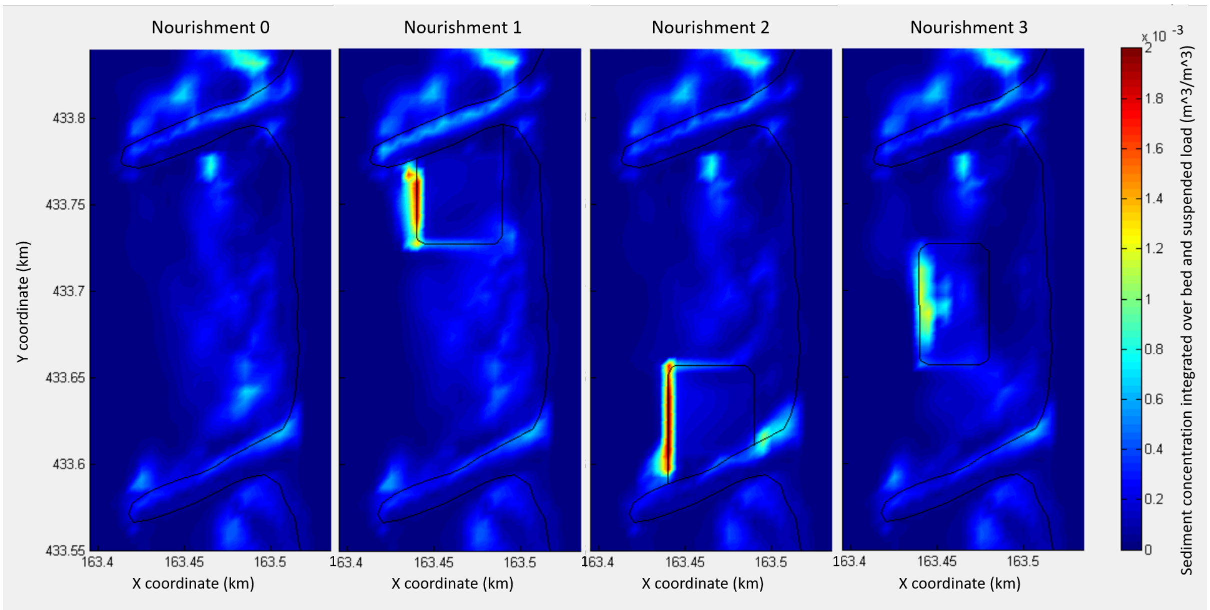


Figure M.3: Mean sediment concentration in case of navigation and no river discharge

M.2 Low river discharge, no navigation

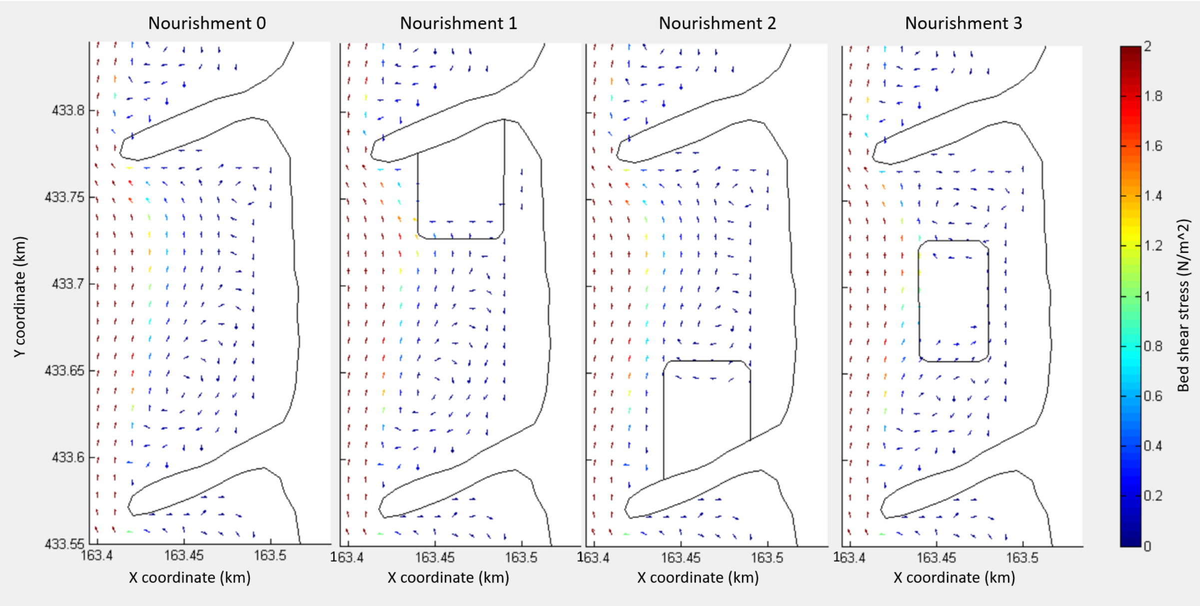


Figure M.4: Bed shear stress in case of low river discharge and no navigation

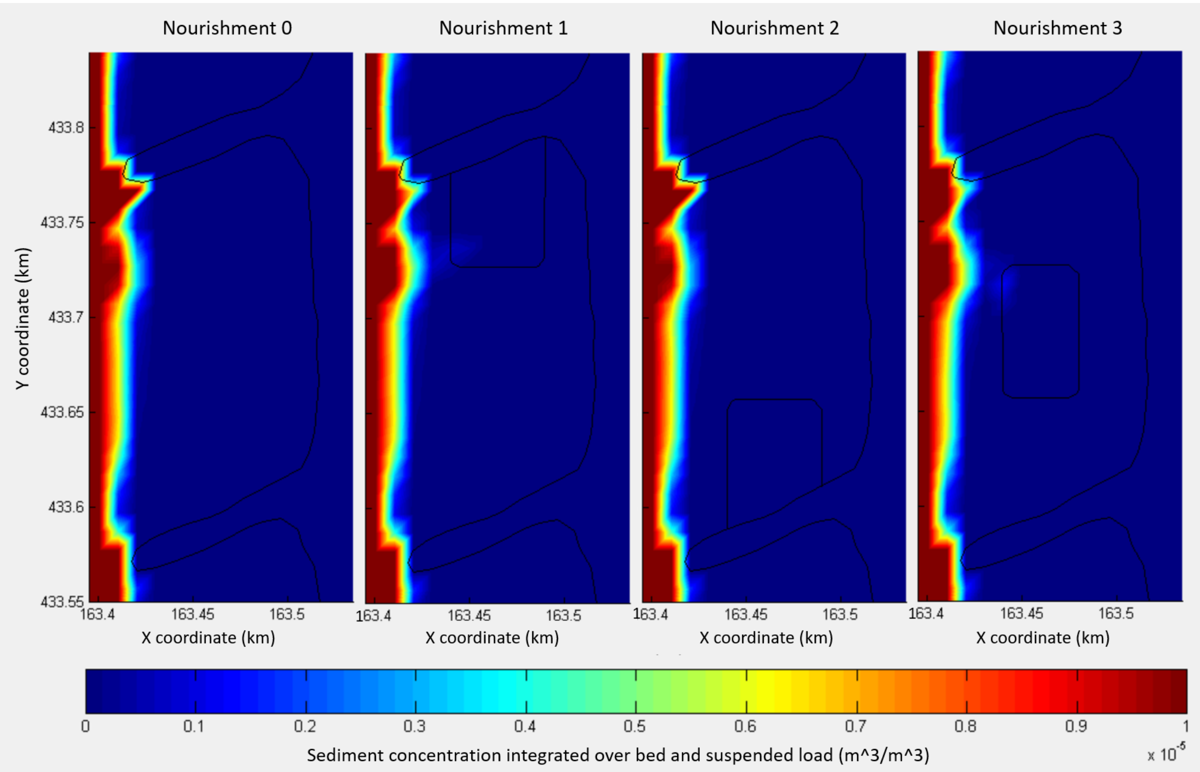


Figure M.5: Sediment concentration in case of low river discharge and no navigation

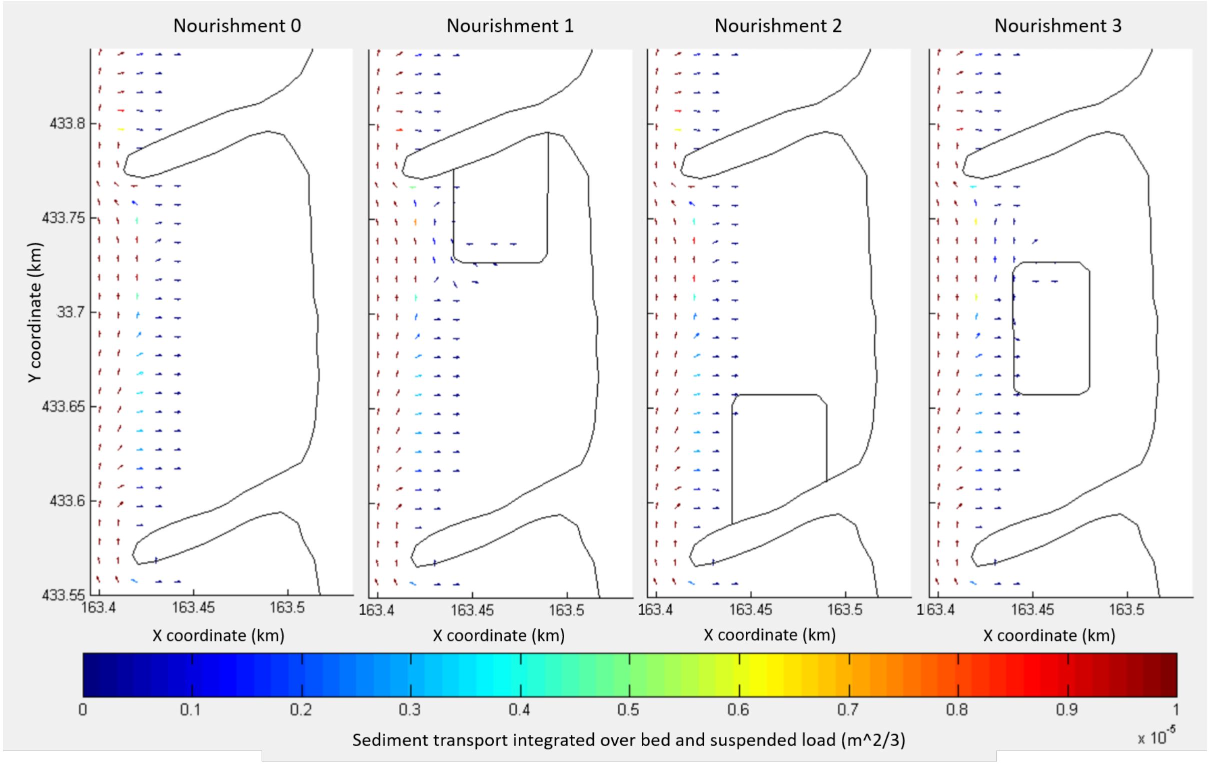


Figure M.6: Sediment transport in case of low river discharge and no navigation

M.3 Middle river discharge, no navigation

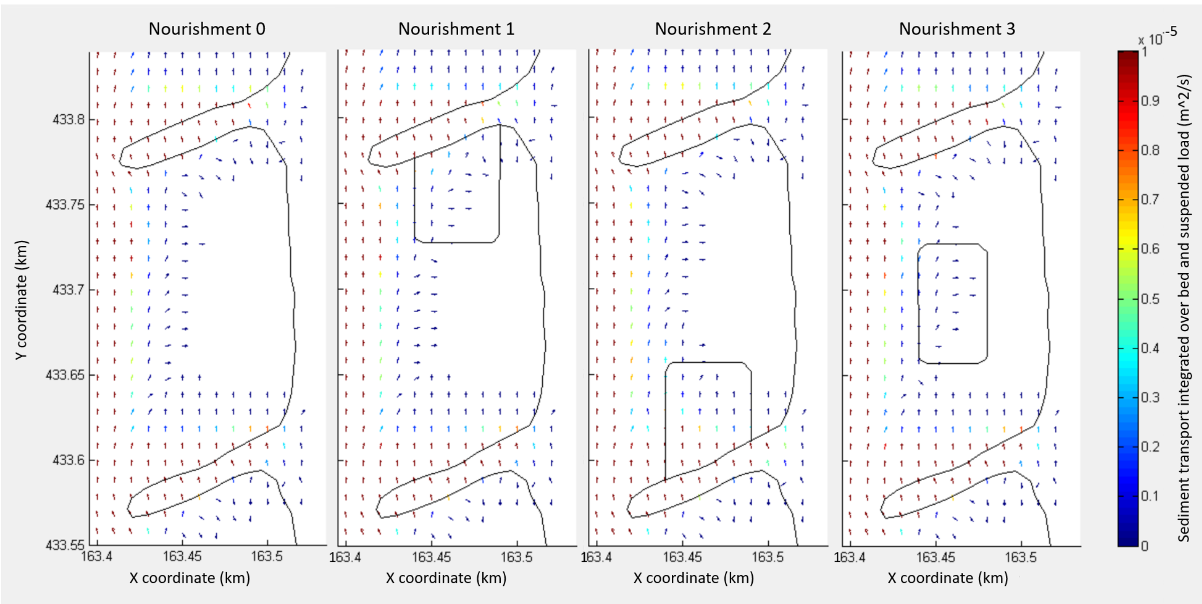


Figure M.7: Sediment transport in case of middle river discharge and no navigation